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AES/SAG 1-2:88-7

**ICE STRESS SENSOR
EVALUATION PROJECTS**

1983/84

March 1986

Canada

Public Works Canada
Architectural and Engineering Services
Technology

AES/SAG 1-4:88-7

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1983/84**

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Preparation Agency:
K.R. Croasdale and Associates

Sponsoring Agency:
Panel for Energy Research
and Development (PERD)
Marine Product Line, Headquarters
Project Manager: M.S. Cheung

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Published by Architectural and Engineering Services
Public Works Canada

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Cat. No. W62-11/88-7E

ISBN 0-662-16299-4



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Canada

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DOCUMENT DATA

1. Document Title ICE STRESS SENSOR EVALUATION PROJECTS 1983/84		2. Control Number AES/SAG 1-2:88-7	
		3. Date MARCH 1986	
4. Author(s) K. R. Croasdale		5. Consultant's Ref. No.	
6. Project Manager M.S. Cheung		7. Discipline Series No.	
8. Preparation Agency and Address K.R. Croasdale and Associates 334-40th Avenue S.W. Calgary, Alberta T2S 0X4		9. Document Type Technical Report	
		10. No. of Pages 158	
11. Sponsoring Agency and Address Panel for Energy Research and Development (PERD) and Public Works Canada, Marine Product Line Sir Charles Tupper Bldg., Riverside Drive Ottawa, Ontario K1A 0M2		12. PWC File No. 6200-31	
		13. PWC Project No. 601061	
14. Supplementary Notes		15. SSC Publication No. W62-11/88-7E	
		16. ISBN 0-662-16299-4	
17. Abstract This report describes two experimental field projects conducted during the winter of 1983/84. Both projects were designed to assess the performance, accuracy and reliability of ice stress sensors. The first project tested five different types of ice sensors under similar conditions in the Arctic ice at the Nanisivik Dock on Baffin Island. Data on ice pressure against Arctic structures correlated with meteorological changes were also collected. The other study was conducted jointly with four oil companies in an open-air test basin in Calgary. Sensors were installed in the ice sheet and controlled-load inputs were applied generating both long-term and short-term stress levels. This report describes both projects and provides detailed results of all tests sponsored by Public Works Canada. Due to screening agreements made with participating companies not all results were made available. The three sensors specified by Public Works Canada at the Calgary project were tested at Nanisivik. The results provide a useful guide to the performance of sensors in terms of accuracy and reliability.			
18. Distribution Statement Copies are available from: Documentation Centre Public Works Canada Sir Charles Tupper Bldg. Riverside Drive Ottawa, Ontario K1A 0M2		19. Keywords Ice forces; ice stress sensors; ice/structure interaction	
		20. Documentation Centre Catalogue No. MA102	21. Price no charge



Travaux publics
Canada

Public Works
Canada

FICHE SIGNALÉTIQUE DE DOCUMENT

1. Titre du document TRAVAUX D'ÉVALUATION DE CAPTEURS DE CONTRAINTES EXERCÉES PAR LES GLACES - 1983-84		2. Numéro de contrôle AES/SAG 1-2:88-7	
4. Auteur(s) K.R. Croasdale		3. Date Mars 1986	
6. Chargé de projet M.S. Cheung		5. No de réf. du conseil	
8. Nom et adresse de l'organisme rédacteur K.R. Croasdale and Associates 334-40th Avenue S.W. Calgary, Alberta T2S 0X4		7. No de la collection technique	
11. Nom et adresse de l'organisme promoteur Comité de la recherche et du développement énergétiques et Travaux publics Canada, Travaux maritimes, Immeuble Sir-Charles-Tupper, Promenade Riverside, OTTAWA (Ontario) K1A 0M2		9. Type de document Rapport technique	
14. Notes		10. Nombre de page 158	
17. Résumé		12. No de dossier de TPC 6200-31	
		13. No de projet de TPC 601061	
		15. No de publication de ASC W62-11/88-7E	
		16. ISBN 0-662-16299-4	
Le présent rapport décrit deux travaux expérimentaux réalisés à pied d'oeuvre durant l'hiver de 1983-1984, tous deux destinés à évaluer le rendement, la précision et la fiabilité de capteurs de contraintes exercées par les glaces. Dans le premier cas, cinq genres de capteurs différents ont été soumis aux essais sous des conditions analogues dans les glaces arctiques, au quai de Nanisivik (Ile de Baffin). Au cours de la même étude, des données touchant la pression des glaces sur les ouvrages arctiques en corrélation avec les changements météorologiques ont été recueillies. En collaboration avec quatre sociétés pétrolières, l'autre étude a été réalisée dans un bassin d'essai à ciel ouvert, à Calgary. Les capteurs ont été installés sur la couche de glace et des charges contrôlées ont été appliquées pour provoquer des niveaux de contraintes à court et à long terme. Le présent rapport décrit ces deux études et donne les résultats détaillés de l'ensemble des essais commandités par TPC. En raison de certaines ententes de sélection passées avec les sociétés participantes, les résultats ne sont pas tous publiés. Les trois capteurs précisés par TPC pour l'étude de Calgary ont été éprouvés à Nanisivik. Les résultats obtenus offrent des renseignements utiles sur le rendement des capteurs sur le plan de la précision et de la fiabilité.			
18. Diffusion Exemplaires disponibles du: Centre de documentation Travaux publics Canada Imm. Sir-Charles-Tupper, Prom. Riverside OTTAWA, Ontario K1A 0M2		19. Mots clés Forces exercées par les glaces interactions glaces/ouvrages	
		20. No de catalogue du centre de documentation MA102	21. Prix Gratuit

MTP 2398 (86/09)

PREFACE

This report is one of several reports on research work in the field of Marine Engineering, identified and managed by the Marine Product Line and Technology Resources groups of Public Works Canada, with funds provided by the Interdepartmental Panel on Energy Research and Development (PERD).

PERD was established in 1974 to coordinate research on energy by the Federal Government with objectives to provide, in conjunction with efforts in the private sector and the provinces, the technical basis for:

- maintaining oil self-sufficiency over the short term, in view of dwindling conventional supplies;
- developing a diversified energy economy, less dependent on oil and gas in the mid-term; and
- making Canadians less reliant on non-renewable energy sources in the long term.

The research work undertaken by Public Works Canada in Marine Engineering with funds from PERD has been directed particularly toward the following two main topics:

1. Ice/Structure Interaction
2. Construction and Towing of Reinforced Concrete Caissons in the Arctic

This report is being published with a view to enhancing the technology in the field of Marine Engineering and contributing toward the objectives of PERD.



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1.0 INTRODUCTION

Ice pressure sensors and strain meters are used for both research purposes and as operational tools, around arctic offshore structures, and around docks and other marine structures, at various places in Canada.

There are a variety of generic types of ice sensors ranging from ice pressure panels to strain meters. Also, there are various designs, each with their own characteristics.

It is important both for suppliers and for organizations which use the results from ice sensors, that their performance be well understood; especially from the point of view of accuracy and reliability. During the winter of 1983/84 Public Works Canada funded two studies aimed at this objective.

One study, funded entirely by Public Works, was a field program conducted in the Arctic at the Nanisivik Dock on Baffin Island. In this study, five different types of ice sensor were deployed close together in the ice in front of the dock. The general objective of the study was to compare results obtained from the five sensors. The rationale being that they should all be subject to similar ice pressure events and that direct comparisons could be made between sensors. This study was also aimed at collecting ice pressure data against an arctic structure and at correlating ice pressure events with environmental events such as storms, tides and temperature changes. The study was also aimed at assessing how well the ice sensors and data acquisition systems performed in the arctic environment, unattended for several months.

It was recognized that in this field project no independent check of ice load or stress in the ice would be obtained, so that if all sensors gave different results no conclusions could be drawn as to accuracy. Also it was recognized that no control could be exercised on the stress levels and time of load application in the field program. Nevertheless it was considered to be a valuable exercise because of the real arctic conditions prevailing.

The other study was conducted in Calgary in the large open-air ice test basin at Esso Resources Canada. This project was conceived and directed by K. R. Croasdale and Associates Ltd. and was funded by four oil companies in addition to Public Works. Each participant was allowed to specify three sensors to be used in the test program. This resulted in ten types of ice sensors being evaluated (note some participants specified three of one type).

On joining the project Public Works specified three types of ice pressure panel which were also being evaluated at Nanisivik. In the ice basin tests, the ice sensors were installed in an ice sheet which could be subject to controlled load inputs. Therefore in this experiment there was little doubt about the stress level being applied to the sensors. Also the time of loading could be controlled so that both long term (creep) and short term stress levels could be generated.

The two projects therefore can be considered complementary, and taken together they constitute the most exhaustive set of tests yet conducted to assess the accuracy and reliability of ice sensors.

All the sensors at Nanisivik and those sponsored by Public Works in the ice basin were of Canadian Manufacture.

This report describes these two ice sensor projects in terms of specific objectives, scope, and results. It should be noted that because of the joint-industry nature of the ice basin tests, that only the results from those sensors sponsored directly by Public Works can be included in this report. The total set of results from all sensors tested will however be made public before the end of 1985.

2.0 SUMMARY

Two projects were conducted to evaluate the performance of in-situ ice pressure sensors and strain meters. One project was conducted in the Arctic at the Nanisivik Dock. There, four different types of ice pressure sensor and one strain meter array were installed for a period of 3 months. The general objectives of the Nanisivik project were to evaluate sensor performance under arctic conditions, and to compare results obtained from a variety of sensors installed at the same location. The results obtained are described in detail in separate reports compiled by the individual sensor suppliers. In this report an overview of the results obtained is presented, and the readings from the various sensors are compared. The plausibility of the results from the various sensors is reviewed in relation to the ice conditions prevailing during the monitoring period. Due to the complex nature of the stresses in the ice at the dock and the presence of numerous tidal cracks it has not been possible to draw any absolute conclusions as to the accuracy of the results from the various sensors.

In the second project however it was possible to evaluate the accuracy of a variety of in-situ ice sensors. This project was conducted in a large open air ice test basin in Calgary. It was possible to induce known stresses in the ice and compare the outputs from the sensors with the known stresses. It was concluded from the ice basin tests that the theories of design and interpretation of ice sensors are reasonably sound, even in a creeping material such as ice. Certain practical considerations however need to be recognized when using different sensor types, and those are discussed in the report. In general it is considered that the ice basin experiment was quite successful. A total of 22 separate load tests were performed with ice stresses up to about 700 kPa. Both short-term and long-term load cycles were applied. It was concluded that the average percentage difference between actual ice loads on the reaction structure and those predicted from the ice sensor readings was better than about 30%.

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3.0 JUSTIFICATION

Ice pressure panels and strain meters have been and continue to be used extensively around artificial islands and caisson systems in the Beaufort Sea and around docks and other marine structures at various places in Canada. The readings from these sensors are used to predict stresses in the surrounding ice and the total loads on the structure. This ice load data is gathered partly to calibrate design criteria and partly to provide real-time indicators of load on the structure which can then be incorporated into operational safety procedures. In both cases, it is obviously very important that the readings from the sensors are reliable, accurate and can be properly interpreted.

In petroleum operations, it is not untypical for several millions of dollars to be invested at a single location on the installation of ice pressure sensors which are placed either on the structure or in the surrounding ice. Furthermore, the influence on the drilling operation of sensor readings can also be in the form of million dollar decisions, e.g. whether to suspend drilling based on the load levels on the structure. Finally, any changes in design criteria for future systems based on sensor readings could result in significant savings, but only if the readings can be interpreted with confidence.

Another important application of pressure sensors is around artificially constructed ice pads which are often placed close to caisson systems to provide relief well capability. It is only possible to instrument these pads to measure applied loads by using ice pressure sensors placed around them. Furthermore, the readings can be very critical in convincing regulatory agencies that the ice pad is adequate and that operations from it can respond to real-time indicators of load and stability.

The user of ice pressure sensors and strain meters is faced with a difficult choice of selecting a type which will give the best possible data in a reliable, cost-effective way.

It is well known that in-situ ice pressure sensors can be difficult to interpret because their inclusion in the ice affects the stress state being measured. This issue is further complicated by the time-dependent characteristics of ice deformation and by the variability of ice deformation properties with temperature. Similarly, the steps required for interpretation of surface strain meters also involve knowledge of material properties and therefore uncertainty is also involved in their interpretation.

More specifically, potential problems of interpretation can be listed as:

- Verification of inclusion factors,
- effect of ice properties on inclusion factors, e.g. modulus variations and creep
- Stress concentrations,
- variation of stress through the ice sheet,
- temperature effects due to sensor characteristics changing, or the effect of differential thermal expansions,
- the effect of biaxial stress states on uniaxial sensors.

Many investigators and sensor suppliers have performed certain in-situ tests in the past. In some cases, the sensor has simply been put into an ice block which is tested in a press. In other cases, sensors have been deployed in front of indenter-type loading faces or flatjacks. These tests have added confidence to the inclusion factors and interpretation procedures for the sensors. However, to our knowledge, there had not been a definitive test where sensors of various types were compared in a set-up where there was an ability to measure and control total load in the ice sheet. Neither had there been a comparison of sensors in the Arctic at the same location. The two projects described in this report were aimed at doing both of the above.

4.0 THE THEORY OF ICE SENSORS

At first sight it seems a relatively simple matter to measure in-situ stresses in an ice sheet. Why not simply measure strain and convert to stress using a value of modulus for ice? Alternatively, why not install a hydraulically filled flat jack in the ice connected to a pressure transducer and measure the pressure on it as the ice is stressed? Both of these approaches are simple, and have been used with other materials including soils and rock; what are the issues relating to their use in ice?

First, the simple conversion of strain to stress in ice is fraught with difficulty, because ice is not a linear elastic material. Ice is a material close to its melting point and therefore exhibits creep. When ice is loaded with a constant stress it initially deforms elastically [i.e. if the load is removed the strain returns to zero] but after a few minutes [or less] the ice creeps. Initially with time there is a primary creep phase in which the strain rate is decreasing with time; this is followed by a secondary creep phase in which the strain rate is constant; and finally there is a tertiary creep phase in which the strain rate increases to failure. These different creep regimes make the interpretation of a simple strain measurement extremely difficult. Especially because the elastic and creep deformation characteristics vary with ice temperature, crystallography, salinity and stress level. In fact it is generally recognized by proponents of strain meters that ice stress can only be sensibly interpreted once the ice is in secondary creep, and then there is a unique relationship between strain rate and stress according to Glen's law;

$$\dot{\epsilon} = A\sigma^n \quad (1)$$

where $\dot{\epsilon}$ is strain rate; σ is stress, n is equal to about 3, and A is a coefficient depending on ice characteristics such as temperature, salinity and crystal structure. Thus strain meters, according to the theory of ice deformation may only be useful to measure loads applied long enough for secondary creep to be established [about 45 minutes or more].

Because of these perceived difficulties, ice engineers have pursued the concept of an in-situ stress sensor which would be insensitive to varying ice deformation characteristics resulting from creep and the effects of varying ice properties such as temperature, salinity and crystal structure.

To insert a sensor into an ice sheet and interpret the results however has other problems which need to be addressed. First, an inclusion in an ice sheet can lead to

a disturbance of the stress field such that the stress experienced by the sensor is different from the stress in the sheet had the sensor not been there. This problem has been addressed by several investigators [Metge et al, 1975; Templeton, 1981; Chen, 1981] and elastic theories have been developed which relate sensor stiffness and geometry to the modulus of the surrounding material.

Typical results from this theory of inclusions are reproduced in Figure 1. The results show obviously that the ideal sensor should have the same modulus or stiffness as the ice. So why not build sensors according to such a specification? The problem is the one discussed earlier that the relationship between stress and strain [modulus] for ice is complex and there is no unique value. Ice modulus varies with temperature, salinity, crystal structure and, because of creep, with time of loading. Therefore the ideal sensor should read the ice stress regardless of the modulus of the surrounding ice. How can this be achieved?

The first attempt to rationalize sensor design was described by Metge et al [1975]. A wide thin sensor was proposed with sufficient stiffness such that as the effective ice modulus varied, the ratio between ice stress on the sensor and stress in the ice remained constant. As can be seen from Figure 1, this should result in an inclusion factor [stress ratio] remaining close to 1.0. This then would be the ideal sensor form, and it is the reason why several sensors of this type have appeared.

The equation for Figure 1 is of the form: [Chen, 1981]

$$\frac{\sigma}{\sigma_i} = \frac{\frac{E_i}{E} + \frac{H}{2D} \left(\frac{N}{E} \right)}{\frac{E_i}{E} \left(1 + \frac{H}{2D} \frac{N}{E} \right)} \quad (2)$$

where

- σ is the undisturbed stress in the ice
- σ_i is the average stress felt by the sensor
- E is the elastic modulus of the ice
- E_i is the elastic modulus of the sensor
- D is the width or diameter of the sensor
in a direction perpendicular to the stress
- H is the thickness of the sensor in the
stress direction
- N is a property of the ice such that
is analogous to the subgrade reaction.

Chen recommends that the value of N be taken as 1.0 based

on both theoretical and experimental examination of the problem.

This then results in equation [2] reducing to

$$\frac{\sigma}{\sigma_i} = \frac{\frac{E_i}{E} + \frac{H}{2D}}{\frac{E_i}{E} \left(1 + \frac{H}{2D}\right)} \quad (3)$$

This is very similar to the one proposed by Metge et al [1975] and yields a graphical result very similar to Figure 1.

Templeton [1981] provided a very thorough analysis of the embedded ice sensor problem and confirmed the use of an equation similar to [3]. He also examined the effects of differential thermal expansion and the effects of transverse pressure [bi-axial stress], and developed equations for their effects. He concluded that their effects on sensor accuracy could be minimized by maximizing the width-to-thickness ratio, i.e. using a thin wide sensor.

Despite this sound theoretical and practical basis for thin wide sensors, others have developed symmetrical cylindrical sensors. These have the advantage of bi-axial capability and can usually be inserted into an augered hole.

The theory of biaxial cylindrical sensors has been developed and reported on by Cox and Johnson [1983].

Their analysis yields, for a very stiff sensor, a value of $\frac{\sigma_i}{\sigma} = 1.5$ which is the same result as given by equation [3]. What this means is that a stiff cylindrical sensor should have an inclusion factor of about 0.67 to obtain values of undisturbed ice stress. However their interpretation is not as simple as this, because of the biaxial nature of the gauge. Readers are referred to the report of Cox and Johnson [1983] for the full theoretical treatment.



5.0 SENSOR TYPES AND HISTORY

The first in-situ ice pressure sensor [known to the author] was developed at the University of Alaska in the early seventies [Nelson, 1975]. The University of Alaska sensor was a small stiff sensor based on a strain gauged metal cylinder. About the same time, the National Research Council in Ottawa developed a small soft sensor based on a thin walled metal cylinder [Frederking, 1980].

Esso Resources Canada contracted the University of Alaska to install some of its sensors around some of the early artificial islands in the Beaufort Sea. Perceived difficulties in interpretation of a small stiff sensor led Esso to develop the wide thin soft sensor which was subsequently used quite extensively by Esso around its islands [Metge et al, 1975].

The Esso sensor was subsequently improved upon by Exxon who maintained the geometry of the Esso sensor but redesigned the internals to achieve better linearity and a different stiffness [Templeton, 1979; Chen, 1980].

During the late 1970's and early 1980's, a large variety of sensors started to appear. The original Esso design was again used as the basis for the MEDOF panel used by Dome around the Tarsiut island [Pilkington, 1983]. Oceanographic Services developed a small cylindrical hard sensor which could be installed in a hole cored in the ice sheet [Johnson and Cox, 1980]. ARCO Oil and Gas Company developed a sensor based on the flat jack principle [McBride, 1981]. More recently, Arctec Canada has built a thin-wide metal sensor called the Hexpack [Graham, et al, 1983]. A hexagonal cylindrical sensor is also being developed by CMEL. Weir-Jones have also developed a wide thin sensor.

In terms of generic types, most of the above sensors can be considered to fall into two broad categories;

- thin wide sensors with a stiffness close to that of ice, and
- small stiff sensors

In a category of its own is the ARCO hydraulically filled disc, which is thin in relation to its diameter, but is small (about 4 inches in diameter) in relation to the ice thickness.

The thin wide panel sensors are generally arranged to measure the ice stress through the full ice sheet thickness; the small sensors usually measure stress over a small area, and therefore, several may be needed through the ice sheet thickness in order to obtain an integrated stress of load. Thin wide sensors can usually only measure stress in one direction, small cylindrical sensors can measure the principal stresses and

directions. Of course any uniaxial sensing unit can be arranged in a rosette to enable principal stresses at a point to be measured.

Another generic type of instrument is the surface strain meter [Goodman, 1980, 1983]. The types most commonly used today are based on an invar wire or rod and a linear variable differential transformer. This type of strain meter was originally developed at the Scott Polar Institute in Cambridge, England. BP have made extensive use of strain meters to infer stress states in ice surrounding islands in the Beaufort Sea. Instrumar in Canada also produce a strain meter based on the Scott Polar System.

Each sensor type has its advantages and disadvantages. Users of sensors are often uncertain about how different sensors may perform under a variety of load and ice conditions. The projects reported here were an attempt to see how the various sensor types responded to known ice loads and to similar field conditions.

6.0 STUDY OBJECTIVES

Each of the studies reported had different objectives but can be regarded as being complementary, in terms of the general objective of better understanding the technology and performance of ice sensors. The specific objectives for each study were as follows.

6.1 OBJECTIVES OF THE ICE BASIN TESTS

"To evaluate the performance of various generic types of ice pressure sensors and strain meters in terms of their ability to measure known ice stresses generated in a large saline ice basin [60 m x 30 m] under known conditions of load and boundary conditions."

6.2 OBJECTIVE OF THE NANISIVIK FIELD TESTS

"To collect ice stress and strain data in the ice at the dock at Nanisivik over a period of about three months using a variety of ice sensors".

"To compare the results from the various sensors and provide an assessment of sensor performance reliability and economics."

"To document ice conditions, weather and tide data; and to provide an interpretation of ice pressure events in relation to these parameters."

7.0 SCOPE OF THE STUDIES

7.1 SCOPE OF THE ICE BASIN TESTS

For this project, use was made of the large Esso test basin in Calgary. The test basin is approximately 30 m wide by 55 m long and during a typical Calgary winter an ice sheet of between 0.5 to 0.9 m can be grown. Loads can be applied to the ice sheet through a loading boom and can be reacted against a simulated structure at the other end of the basin.

The general concept was to allow the ice sheet to grow to about 0.5 m thick with ice sensors placed in the ice sheet at locations close to the reaction face. A known load was applied to the ice sheet [using loading rams] and was reacted against the vertical structure about 3 m wide at the end of the basin (Figure 2).

The loading pattern in terms of magnitudes and duration was quite varied. With this arrangement, loads of up to 200 tons could be generated. Various load levels could be applied either for short times (Minutes) or long times (hours). This experimental set-up is described in more detail in the full project report (K. R. Croasdale and Associates, 1984).

It was recognized early on in the project that the stress in the ice would be a maximum at the reaction face (1150 kPa or 167 psi at maximum load) but would decay to lower values at points away from the structure. This of course is the situation in real life if sensors are placed in an ice sheet some distance from a structure. However for this experiment it did present a dilemma in terms of knowing the ice stress which a particular sensor should be seeing at a given load. To address this issue two measures were taken. First a stress distribution was calculated using an elastic finite element approach (described in the full project report). Second, the final tests were done with the ice sheet slotted so that theoretically the sensors in front of the structure would all be subject to the same stress.

In all, a total of 22 tests were performed and ten sensor types were included in the experiment.

7.2 SCOPE OF THE FIELD TESTS

Public Works Canada contracted five organizations to install ice sensors in the ice off the dock at Nanisivik. Typical terms of reference for these contractors were:

- [1] Calibrate ice force sensors prior to installation
- [2] Carry-out in-situ calibration in the field

- [3] Install the ice sensors and data acquisition system at Nanisivik
- [4] Record ice stress [strain] data either continuously or at least once per hour
- [5] Collect data for about three months
- [6] Process the data
- [7] Prepare a report describing the sensors; the data acquisition system; installation; field observations; raw and processed data; conclusions and recommendations.
- [8] Supply details and specifications of the sensors.

The contractors and sensor types involved in this project were as follows:

Arctec Canada	- Hexpack ice pressure panel
Canada Marine Engineering Ltd.	- Hexagonal biaxial stress sensor
C-CORE	- Instrumar" strain meter array
FMS Engineers	- MEDOF ice pressure panel
Weir-Jones Engineering Consultants Ltd.	- IDEAL ice pressure panel

As mentioned earlier, K. R. Croasdale and Associates Ltd. was contracted to act as overall coordinator for the study and in particular to prepare a comprehensive report comparing the results from the various devices.

Each contractor has submitted it's own report on the results obtained, these reports are listed in the references. Certain selections from them are reproduced in this report where appropriate.

8.0 DESCRIPTION OF SENSORS USED IN THE PROJECTS

Those sensors that were installed at Nanisivik are described here but these were also tested in the ice basin. The results from other sensors tested in the ice basin cannot be made public until the end of 1985, and are therefore excluded from this report.

The sensors are presented in alphabetical order. [For more details of the sensors consult the individual contractor reports].

THE ARCTEC HEXPACK PANEL

The Arctec Hexpack is a thin wide metal sensor, usually about 1 m wide and about 22 mm thick. The individual sensing units consist of strain gauged metal buttons formed into a hexagonal array. The panel stiffness is about 1.6 GPa [240,000 psi].

The sensor can be arranged such that horizontal strips of the sensor are wired into separate full bridge configurations. This way the ice pressure distribution through the ice thickness can be measured.

The Hexpack used in the ice basin project was 1 m x 2 m [see Figure 3], it weighed about 80 kg. The Hexpack used at Nanisivik was smaller, about 1 m x 1 m, it weighed about 40 kg.

The Hexpack measures ice pressure acting perpendicular to its width.

CANADA MARINE ENGINEERING CMEL Mark 1V - C Sensor

The CMEL Mark 1V-C is a cylindrical hexagonal sensor about 10 cm in diameter and 28 cm long, [see Figure 4]. It has a stiffness of about 31 GPa and can resolve the stress into principal stresses and directions. It works on the principle of strain gauged load bars positioned across opposite faces of the hexagon.

C-CORE: INSTRUMENT STRAIN METER ARRAY

This consists of three 1 m gauge length invar wire strain meters. The wire is held in tension between a lever/weight mechanism and a range reset servo motor. A linear variable differential transformer senses displacement as amplified

by the lever system. The minimum resolution claimed for this instrument is 0.2 micron. The design was originally developed at the Scott Polar Research Institute in England.

Figure 5 shows the strain meter array in position on the ice at Nanisivik.

FMS - MEDOF ICE PRESSURE PANEL

The internal structure of the Medof panel is similar to the original Esso design consisting of two metal plates separated by elastomer buttons. Hydraulic fluid is contained within the interstices between the plates. When stressed, the elastomer buttons compress and the fluid is expelled into a vertical tube. A pressure transducer measures the head of the fluid displaced.

The panel is thin and wide. At Nanisivik two panels 1 m x 2 m x 21 mm were employed. One had a stiffness of 520 MPa, the other 430 MPa.

In the ice basin tests, the panel was 0.5 m by 1.0 m. Its stiffness was about 200 MPa.

Photographs of the MEDOF panel being installed at Nanisivik are shown in Figure 6.

WEIR-JONES/TERRASCIENCE "IDEAL" ICE FORCE PANEL

This is also a thin wide sensor of metal construction. Load carrying modules are sandwiched between steel or aluminum plates. Evenly spaced between the load carrying array are a number of equally stiff load measuring modules which sense the external pressure being applied to the outer plates. A typical thickness is 20 mm. In the basin tests a 0.5 m by 1 m panel was used. At Nanisivik two panels were used one was 1 m x 1 m; the other was 1 m x 2 m. The mass of the panels is about 60 kg/m².

These panels can also be wired to give stress distribution through the ice as well as average across the panel depth.

Figure 7 shows an Ideal panel prior to installation at Nanisivik.

9.0 THE NANISIVIK FIELD TESTS

Sensor installation took place during the period December 28th to January 2nd, 1984. Sensor removal took place at the end of March, 1984. The reader is referred to the individual contractor reports (see references) for greater details of the individual sensors, their deployment, results and interpretation, than is given in this overview report.

9.1 LOCATION DESCRIPTION

The test site was chosen by Public Works, Canada. There are good reasons for choosing the Nanisivik dock location. First of all the dock was designed by Public Works, Canada [Gigrah and Shah, 1978] and this is one of the few marine structures in the Arctic. Therefore there was an interest to collect information on ice action against it. Second, the ice conditions and forces on the dock had been the subject of several winters of studies by the National Research Council [Frederking and Nakawo, 1981]. Because of these studies good background information was available on the types of ice conditions and stress levels to be expected. The third reason why the Nanisivik dock is a good site is because of the logistics support available from Nanisivik Mines which operates year-round.

Nanisivik is located on Strathcona Sound which branches off Admiralty Inlet at the north end of Baffin Island. The dock consists of three sheet-piled cells located about 75 m offshore, each cell is about 20 m in diameter. The cells are filled with local aggregate and capped with a 0.3 m thick concrete deck. The cells connect with each other by a rock-fill apron and are joined to the shore by a causeway [Figure 8]. Water depth at the outer edge of the cells is 13.5 m.

As Frederking describes "the Sound is usually covered by land-fast first-year ice up to 1.6 m. thick. Freeze-up commences mid to late September, reaching an ice thickness of 0.4 to 0.5 m. by the beginning of November. Occasionally there may be late autumn intrusions of multi-year ice floes, which become frozen into the ice cover and go out with the first-year ice in the spring. One small iceberg has remained in the sound since 1975. The winter ice cover is quite stable; the only visible features are tidal hinges along the shore. No pressure ridges have been observed in the period of 1975 to 1982."

The maximum tidal range in the sound is about 2.5 m. It is this tide, causing the ice to lift up and down, which appears to create the active ice zone at the dock. A general

description of this active zone is given by Frederking [1981]; "Shortly after freeze-up an ice bustle forms on the vertical face of the cells. The sea water freezes and adheres in layers to the sheet piles between the high and low tide levels, forming a parabolic shaped protuberance. This feature may extend a metre out from the cell by mid-November. Between the level first-year ice and the bustle is a zone about 2 m. wide which is subject to some surface flooding and becomes thicker than the first-year ice. By the February-March period, the active zone has evolved to about 2.5 times the thickness of the level ice and about 8m wide [Figure 8]. The bustle is no longer present and is most likely incorporated into the active zone. The first-year ice is curved up where it reacts with the active zone."

In earlier papers Frederking [1980] showed the bending deflections in the sheet ice to extend out about 16 m by the end of March.

During this project ice conditions observed were similar to those seen by Frederking and are described in Section 9.5. The selection of the area to place the sensors was based on observations at the site December 28th to January 2nd and on Frederking's descriptions of the typical ice conditions by the end of March.

9.2 SENSOR DEPLOYMENT AND REMOVAL

The general location area of sensor deployment in relation to the Nanisivik Dock is shown in [Figure 9]. Sensors were generally spaced about an imaginary line running offshore from the centre cell of the dock. The distance from the centre cell to the line of sensors was 21 m. (This distance had increased to 24.5 m by late March). The sensors were set back about 13 m from the active zone in the level ice. At the time of installation the thickness of the level ice was in the range 0.7 to 0.9 m.

Within the zone of deployment, sensors were arranged across a width of about 22 m as shown in [Figure 10]. The rationale for this arrangement being as follows:

- * Sensors to be at least 2 m apart spaced along a line of what might be expected to be a uniform stress contour. [Note that analysis of stress disturbances in ice around sensors indicate that for most sensors any stress disturbance is dissipated within about 1 m from the sensor; see [Chen, 1980; Cox and Johnson, 1983].

- * The sensors to be in the relatively undisturbed level ice sheet, i.e. not in the active tidal zone. Also to be far enough back to avoid extreme flexural deflections due to tide yet close enough to the dock to give an indication of compressive force acting on it. [As mentioned, a distance of 21 m from the dock was chosen].
- * Sensors to be as close together as possible in the central zone opposite the central cell of the dock.

The above criteria had previously been discussed and agreed to with both R. Frederking of NRC and M. Cheung of Public Works.

With respect to deployment of sensors of similar type, it was decided that the "Medof" panels should be arranged one with the long axis vertical and one with the long axis horizontal [but both facing the dock]. It was also agreed that the small "Ideal" panel should be placed at right angles to the large one [which faced the dock].

Prior to sensor installation the snow was cleared from the ice in the area of deployment, the snow was about 15 cm [Figure 13].

As illustrated in the photographs Figures 14 and 15, the panel sensors were installed by first cutting a slot completely through the ice with a chain saw. A second slot was then cut about 10 cm away and the ice between chipped out with an ice chisel. The time for this operation obviously depends on the width of sensor and the ice thickness; typically at Nanisivik cutting the slot for a panel took about 30 minutes.

The ease of installation of a panel into a slot depended primarily on the mass of the sensor [Figure 16]. The use of ropes running underneath a sensor could be used effectively to lower heavy sensors [such as the Medef Panel] into the slot [Figure 17].

Typically, the time to install a panel, including slot cutting, was about one hour.

The cylindrical sensors in this project, the CMEL Mark 1V-C (two) were installed in augered holes. The total installation time of these sensors in the ice at Nanisivik was about 30 minutes. [Figure 18]. The length of the CMEL sensor is 28 cm. At Nanisivik one sensor was installed with the lowest point 46 cm below the ice surface, the other with its lowest point 70 cm below the surface; the total ice thickness being 85 cm.

The strain meters require only surface preparation of the ice [essentially snow clearing]. Total time for strain meter installation [Figure 19] was about ninety minutes.

As depicted in Figure 10, the data acquisition systems were positioned on the ice near to the sensors. Each data acquisition system had its own battery system; some of these were trickle-charged through a charger in the shack [power was available at the dock].

Installation of sensors and data acquisition systems took place in very cold weather [about -40°C]. Complete darkness prevailed at the site during installation, however the lights on the dock were switched on, and a spotlight brought by Weir-Jones was a great help for detailed work.

In contrast, removal of the sensors took place in bright daylight at the end of March. The temperatures during removal being in the range -20 to -30°C .

Except for the strain meters, time for sensor removal was longer than installation. This was because of the greater amount of ice cutting. To avoid contact between chain saw and sensor about 15 cm should be allowed between saw cut and sensor. Also during removal, the effective mass of each sensor is increased by the adhering ice and the large sensors need lifting gear to remove them. During removal the ice was about 1.7 m thick.

During removal, when slots have been cut around each sensor, the zero readings can be rechecked.

Also, prior to removal it is possible to conduct an approximate in-situ calibration using thin flat-jacks installed in the ice about 0.5 m from the sensor.

Description of these calibrations are given in the reports submitted by the individual sensor suppliers.

Figures 20 to 25 show photographs taken during the in-situ calibration and sensor demobilization.

9.3 DESCRIPTION OF DATA ACQUISITION SYSTEMS

The data acquisition systems were required to operate in a "semi-remote" location for a period of about 3 months. However, 110V AC power was available at the Nanisivik dock and was used to trickle-charge batteries. Also, arrangements were made for a local person to change data tapes as required. So although the data

acquisition systems were being tested under appropriate arctic climatic conditions, it was not as severe a trial as a remote arctic location would provide.

Four different data acquisition systems were used in this project, and are described briefly below; [for more details consult the individual contractor reports].

RUSTRAK CHART RECORDER

Two Rustrak chart recorders were used to record strain data from the Instrumar strain meters. These were standard chart recorders powered by a 12V automobile battery [trickle-charged]; few technical details were supplied by the contractor. Each strainmeter had a resolution of 36mV/microstrain, and the recorders had $\pm 5V$ full deflection, so that strains up to 138 microstrains could be recorded before the servo motors on the strainmeter reset.

MICROLOGIC DATA LOGGER [CDL-1]

This was used to record signals from the Medof panels. It is a 16 channel low power system using a digital cassette recording technique. The system is powered by a single external 12V battery and draws 80 milli amps while recording and 800 μ amps in standby. The recording density of the cassette used was 615 bpi which enabled the standard digital data cassette to hold over 120,000 sixteen bit samples. The recorder can scan up to 5 channels per second and the scanning interval can be varied from one second to 999 minutes. In this project the scanning interval was 10 minutes. At this rate the single cassette had sufficient storage for about 45 days of data.

The signal conditioning amplifiers, the data logger and battery were stored in an insulated wooden box.

TERRASCIENCE SYSTEM

This system was used to record data from the Weir-Jones Ideal stress sensors. It consisted of three data loggers, two Terrascience IMS08 Data Loggers and one Micrologic DCL 16 Data Logger. The IMS08s are single channel units but can store up to 16384 data readings per module at sampling rates from 8 seconds to 4.5 hours. Alarmed operation based on rate-of-change is also possible with these units. The CDL logger was added to provide additional channels and storage capability. The contractor's report describes the arrangement of data loggers and signal conditioning equipment in more detail.

THE ARCDATS SYSTEM

The Arcdats was used to record data from the Arctec Hexpack, the CMEL sensors, the tide gauge and thermistor strings. Arcdats is a self-contained micro processor/data recording system designed for harsh environments and remote locations. For additional information and technical details, the supplier (Arctec Canada Ltd.) should be consulted.

9.4 SUMMARY OF RESULTS - NANISIVIK

Results obtained from individual sensors are given in detail in the contractor's reports (see references). Typical outputs from each sensor type, plus typical maximums, averages, stress distributions through the ice thickness, and periods of reliable data are given in the following for each sensor in turn.

9.4.1 The Weir-Jones Ideal Panels

The ice pressure data obtained every 15 minutes from the Ideal panels is typically as shown in Figures 26. The values shown are the average compressive ice pressures on both the 1 x 1 m panel and the 4 ft. x 8 ft. panel. No correction has been made for ice thickness being less than 8 ft. (this will be discussed later). The period covered in Figure 26 is from February 14 to 17 inclusive. February 14 being the first day of data from these panels because of a data acquisition system malfunction prior to that date. The values shown in Figure 26 are typical maximums for the ice pressures measured on these panels. On the 4 x 8 panel the highest panel pressure (averaged over the 4 x 8 area) was about 200 kPa. The 1 x 1 m panel, at right angles to the 4 x 8, measured values up to about 150 kPa.

The cyclic nature of the ice pressure can be seen clearly on Figure 26, and correlates well with cyclic outputs from other sensors and the tides.

The 4 x 8 panel also provided eight separate outputs giving the ice pressure distribution across the panel area. Figure 27 is a sample output of the ice pressures sensed by two areas about 1 m from the ice surface. The period of the data is the same as in Figure 26, i.e. February 14 to 17. Peak pressures reached values of about 400 kPa, and this value was the maximum sensed by the Ideal panels.

Weir Jones also plotted the distribution of ice pressure through the ice thickness, as 16 hour averages. A typical distribution is shown in Figure 28 for February 16 and 17.

9.4.2 The FMS Medof Panels

The Medof panels were both 1 m x 2 m in size, one was

placed with its long axis horizontal (P-10) and one with the long axis vertical (P-18). The Medof panels give the ice pressure averaged over the panel area. No correction was made for ice thickness, but the P-10 which was fully contained within the ice should be giving close to the average ice pressure through the thickness. The P-18 output should have been corrected for thickness.

These panels and their data recording system functioned for the entire period. A typical output for the P-10 panel is shown in Figure 29, for the period January 2 to 28. Figure 30 shows the P-10 output for March. FMS suggest that the lowest values on these plots should correspond to zero which would then imply peak stresses of about 40 kPa during January, and about 80 kPa during March. Again, the strong cyclic pattern of stress correlates well with the other sensors and with tidal action. If true zero is taken as the reading at installation then the peak stress measured during January was about 95 kPa and during March about 150 kPa.

Outputs from the P-18 panel for January are shown in Figure 31. The amplitudes of the cyclic stress variations are less, presumably because the ice pressure is being averaged over 2 m whereas the ice thickness during January was about 1 m. The total ice pressure (assuming a true zero) was also lower than the P-10 output.

9.4.3 The Arctec Hexpack Panel

This was a 1 m x 1 m panel which could indicate ice pressure across 4 instrumented strips down the panel length.

Figure 32 is reproduced from the Arctec report showing peak and averaged strip pressures for the period January 3 to January 14, 1984.

A typical output of the upper strips (1 and 5) is shown in Figure 33 for the Period January 2 to January 6; Figure 34 shows the outputs from the lower strips (3 and 6) during the same period. The 'flat' pattern of the peaks was due to a microprocessor problem and is discussed by Arctec in their report. In fact the results shown in Figure 32 are based on extrapolation of trends prior to and after the 'flat' periods and must therefore be treated with caution.

The pressure traces also show the cyclic pattern observed on other sensors.

Arctec suggest that after January 19 a crack ran through their sensor location and that data obtained after that date further complicates interpretation. But in any case, the pressure readings saturate at about 120 kPa for the whole recording period.

9.4.4 The CMEL Mark IV-C Hexagonal Sensors

CMEL C-1 only ever functioned on one axis. To create a major principal stress output, synthesized inputs for the other two channels had to be provided (see the contractor report). These synthesized inputs were based on the responses from the CMEL C-2 sensor which did function on all three axes. Recognizing this potential error, the major stresses measured by the C-1 sensor are shown typically in Figure 35 for the first two weeks in January. The C-1 sensor was about 0.5 m below the ice surface. The general ice pressure level seen by this sensor was about 800 to 900 kPa.

The major and minor ice pressures seen by the C-2 sensor for the same period are shown in Figures 36 and 37. The general ice pressure level was in the range 300 to 400 kPa. A magnification of the time scale as shown in Figure 38, indicates a strong cyclic output which can be correlated with tidal action. The amplitude of ice pressure during these cycles was about 80 kPa.

9.4.5. The Instrumar Strain Meters

As already discussed these three strain meters were arranged in a rosette and measured surface strain in the ice sheet. Their output was processed to give maximum and minimum strains, and angle. These are presented as both finite [absolute] and incremental values in the C-CORE report. Typical results are shown here as Figures 39 and 40. Also presented in the C-CORE report are finite and incremental dilational and deviatoric strains, plus finite and incremental strain rates. Typical results are shown in Figures 41 and 42. Because of servo motor resets it is recommended that absolute strain values be treated with caution.

9.4.6. Overview of Results

Table 9.1 shows an overview results summary for the ice pressure sensors [the strain meters are not directly comparable]. The results shown in this Table will be discussed further in Section 9.6.

9.5 ANCILLARY MEASUREMENTS AND OBSERVATIONS

Arctec Canada Ltd. was subcontracted by K. R. Croasdale and Associates Ltd. to install instruments to measure tide, ice temperatures, and air temperatures. The tide instrument was a 0-15 psig pressure transducer, the temperatures were measured using themistors. These instruments, their calibration and electronic circuits are described in detail in the Arctic report [see references].

The themistor string performed satisfactorily and the full set of ice and temperature data are given in Appendix A. Temperature profiles through the ice based on these data are shown as Figures 43 and 44.

For comparison with the air temperatures obtained at the dock, the air temperatures recorded at the airport at Nanisivik are also given in Appendix A.

The tide gauge functioned from the time of installation until January 19 when it is presumed that the breather tube and/or the signal cable was damaged by ice action. The results from the tide gauge are given in Appendix B with a typical output in Figure 45. The values obtained by the tide gauge are obviously incorrect as the amplitude shown is only about 0.4 m. It is presumed that this is due to an error in the microprocessor logic. Actual tide values for the same period as calculated by CMEL from the tide tables are shown in Figure 46 [the lowest tide value being given a zero value]. These show about a 3 m tidal range which is compatible with visual observations. Although the amplitude of tide measured with the tide gauge were obviously in error the times of high and low tides appeared to be correct.

Ice thicknesses in the level ice during installation were measured in the range 75 to 85 cm. These thicknesses agree with extrapolation of the temperature profiles to the -2°C value. During removal of the sensors at the end of March the typical measured thickness was about 1.8 m. By extrapolation of the temperature data a similar value is obtained. These thickness values are compatible with those measured by Frederking [1977, 1980, 1981].

Ice conditions around the Dock are obviously dominated by tidal action. The observed conditions during January and March were very similar to those observed by Frederking (1977, 1980, 1981) and as described in Section 9.1. Figure 47 shows photographs of typical ice conditions in March. The extent of the active zone can be seen clearly, it extended about 8 m from the dock in January and about 11 m from the dock at the end of March. A precise measurement from the centre cell to a reference

point in the area of the sensors indicated that the ice was in fact pushed away from the dock about 3.5 m during the period January 1 to March 31. Frederking [1981] reported similar amounts of movement.

9.6 DISCUSSION OF RESULTS

Table 9.1 gives a summary of results obtained from the ice pressure sensors installed at Nanisivik during this project. Although all the sensors show similar trends there is quite a spread of values of ice pressure measured.

In general all sensors showed a strong correlation of ice pressure peaks with tidal variation. Furthermore, it appears that all sensors measured maximum compressive stress in the ice close to the time of low tide.

On the basis of the values of ice pressure measured by the various sensors, it is virtually impossible to comment on the relative accuracy of the various sensors tested. This is mainly because the stress state in the ice near the dock was extremely complex involving both direct compressive stresses and flexural stresses [due to the tidal deflections]. In addition, there were tidal cracks in the ice, some of which passed through the sensor locations. The presence of these tidal cracks also complicates the task of comparing sensor results with plausible values.

In terms of constant compressive stress we might speculate on what level is required to achieve the 3.5 m movement of the ice away from the dock during the period of measurement. The average movement rate was 3.5 m in 90 days which is equivalent to about $4.5 \times 10^{-7} \text{ m s}^{-1}$. Use can be made of indentation theory and the constitutive laws for ice to calculate the corresponding stress in the ice close to the dock for this effective indentation velocity.

Both reference stress creep theory [Ponter et al, 1983] and plasticity theory [Ralston, 1979] give similar expressions for the relationship between indentation velocity [V] and strain rate [$\dot{\epsilon}$] for an indenter of width [D]; typically

$$\dot{\epsilon} = \frac{V}{D}$$

In this case the indenter width might be taken as about 100 m, then the strain rate becomes $1.1 \times 10^{-9} \text{ s}^{-1}$.

Sanderson [1984] gives typical relationships between strain rate and stress in secondary creep. At 10^{-9} s^{-1} strain rate, a typical ice stress at -10°C [zero salinity] would be about

100 kPa. This compares well with the value of 150 kPa calculated by Frederking [1980] assuming the ice movement is absorbed by strain across the width of the Sound.

Furthermore, these values are not inconsistent with the general level of compressive stress measured by the ice pressure sensors. Especially when it is recognized that those calculated from ice movement are based on average strain rate, whereas it appears that tidal jacking will create peak average stresses several times higher than the time-averaged values.

Nevertheless, despite this satisfying rationale, the analysis does not give any basis for determining how accurately the ice pressure sensors functioned during this project. The reader is referred to the second part of this report where the ice pressure sensors were tested under known conditions of stress for an answer to this question.

In general it appears that all sensors functioned satisfactorily during this project. The major problems in terms of data collection were actually with two of the data acquisition systems which malfunctioned and affected data from four of the sensor installations.

The surface strain meter data is not easily interpreted in terms of ice stress because of the superimposition of short-term elastic strains from the tidal action on long-term creep strains due to the sustained compressive stress in the ice sheet. Also the re-zeroing of the strain meters makes estimation of the absolute strains extremely difficult. However the strain meter data appears quite plausible, the tidal flexural deflections being seen clearly on the strain meter data.

In terms of ease of installation and logistics, all the ice pressure panels are similar. Cutting a slot for installation can be accomplished easily using a chain saw. At temperatures common to an arctic winter, they freeze-in within a matter of hours. Removal, however is often difficult because of the large mass of ice surrounding a panel after cutting around it with a chain saw. Depending on the size of the panel, lifting gear might be required. Based on the author's experience at other locations, the use of a portable steamer is a preferred method of sensor removal in the spring. Small diameter cylindrical sensors can easily be installed in an augered hole. Their removal is not so easy, again requiring a chain saw or a steamer. Strain meters can easily be installed and removed.

TABLE 9.1
OVERVIEW OF ICE PRESSURE SENSOR RESULTS
NANISIVIK - JANUARY TO MARCH 1984

SENSOR	PERIODS OF RELIABLE DATA	COMPRESSIVE ICE PRESSURE AVERAGED THRO' ICE THICKNESS (TYPICAL PEAKS) (kPa)	TYPICAL PEAK ICE PRESSURE THRO' THICKNESS (kPa)	INDICATION OF PRESSURE (STRESS) DISTRIBUTION THRO' THICKNESS (kPa)	RELATION TO TIDAL CYCLE	TYPICAL MAXIMUM STRESS AMPLITUDE THRO' TIDAL CYCLE (kPa)
IDEAL 4'x8' panel (summed output)	14 Feb-17 Feb	200 kPa on Feb 14	400 kPa on Feb 15	Highest stresses 1.5m from ice surface	Strong cyclic pattern of ice pressure 2 peaks per day	200 kPa on Feb 14 400 kPa on March 16
IDEAL 4'x8' panel (individual channels)	25 Feb-18 March 14 Feb-30 March	120 kPa on Feb 26 160 kPa on March 4 100 kPa on March 15	300 kPa on Feb 26 380 kPa on March 4 280 kPa on March 15	Next highest 0.6m from ice surface		
MEDOF P-10 MEDOF P-18	Jan 2-March 30	135 kPa on Feb 14 (or 40 kPa depending on interpretation) 120 kPa on Feb 26 (or 30 kPa) 150 kPa on March 26 (or 70 kPa)	NOT APPLICABLE	NOT APPLICABLE	Strong correlation with tidal cycle	40 kPa on Feb 14 30 kPa on Feb 26 70 kPa maximum on March 26
ARCTEC HEXPACK (summed output) ARCTEC HEXPACK (individual channels)	Jan 2-March 15 (But crack thro' ice at sensor about Jan 19)	300 kPa on Jan 3 400 kPa on Jan 6	Up to 1000 kPa (Extrapolated)	Highest stress 0.50 to 0.75m from ice surface	Strong correlation with tidal cycle. High stresses at low tide.	1000 kPa extrapolated (120 kPa maximum measured)
CHEL MARK IV C-1 (0.46m Down) CHEL MARK IV C-2 (0.7m Down)	Jan 2-19 Jan 2-19	About 800 kPa About 300-400 kPa Mean of 2 sensors about 600 kPa	About 800 kPa	Highest stresses in Upper Sensor at 0.5m	Cyclic but high background stress Highest 1-2 hrs before low tide	Typically 80 kPa on Jan 5

IN-SITU STRESS MEASUREMENTS

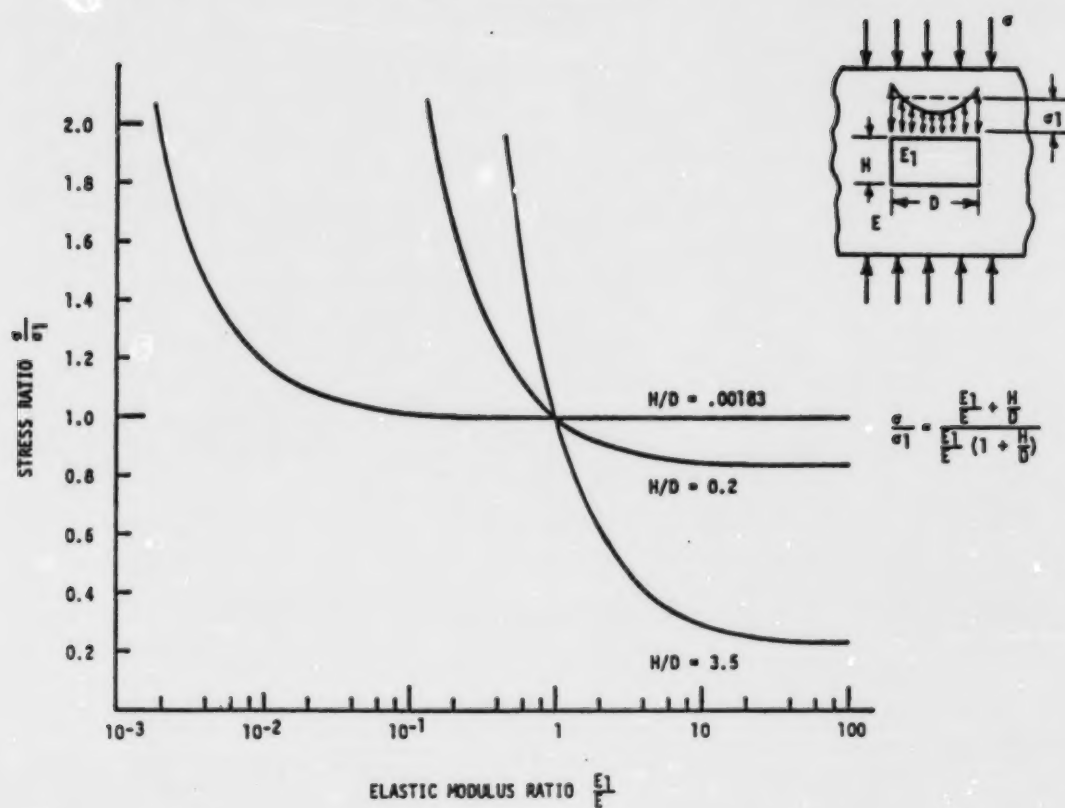
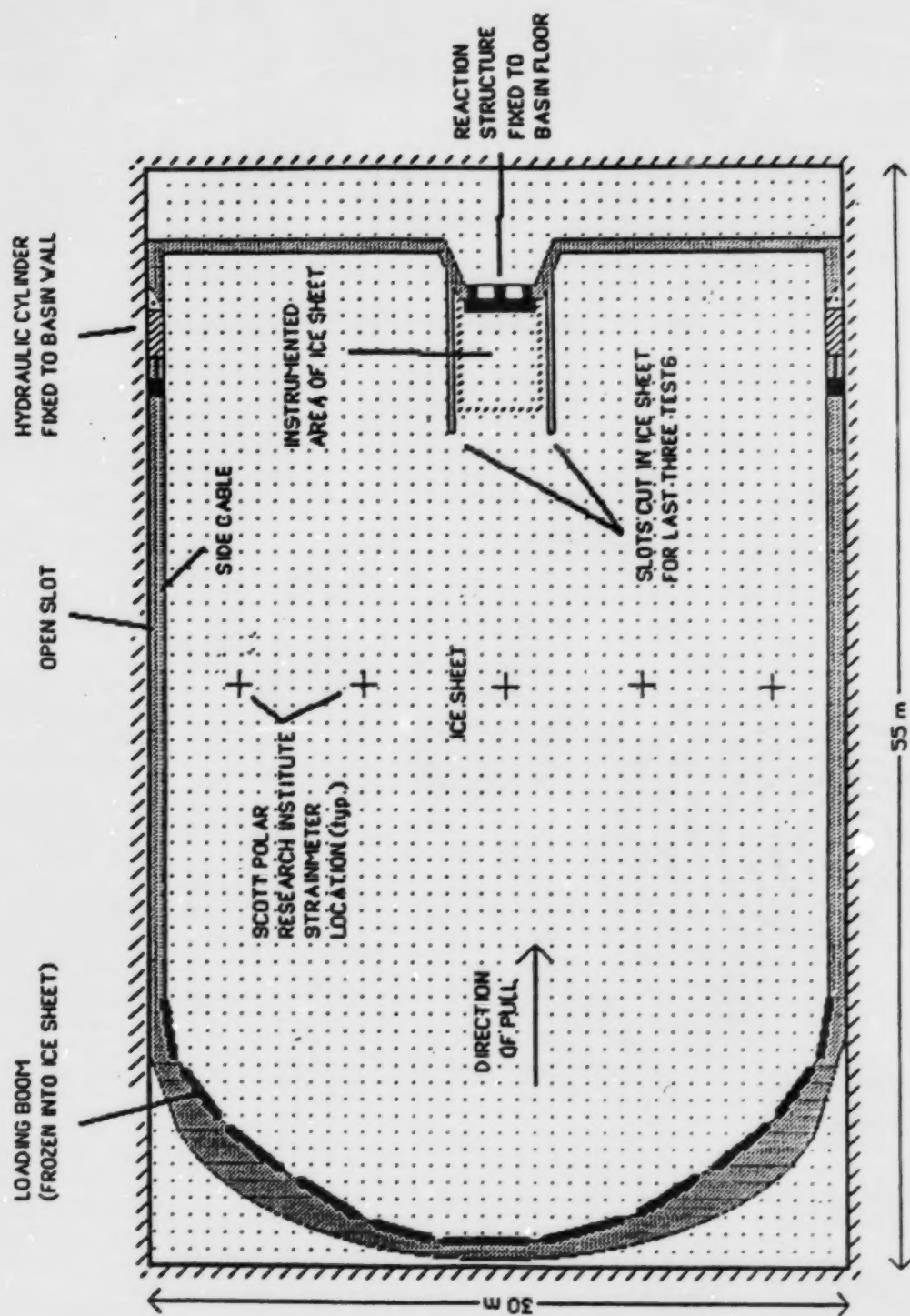
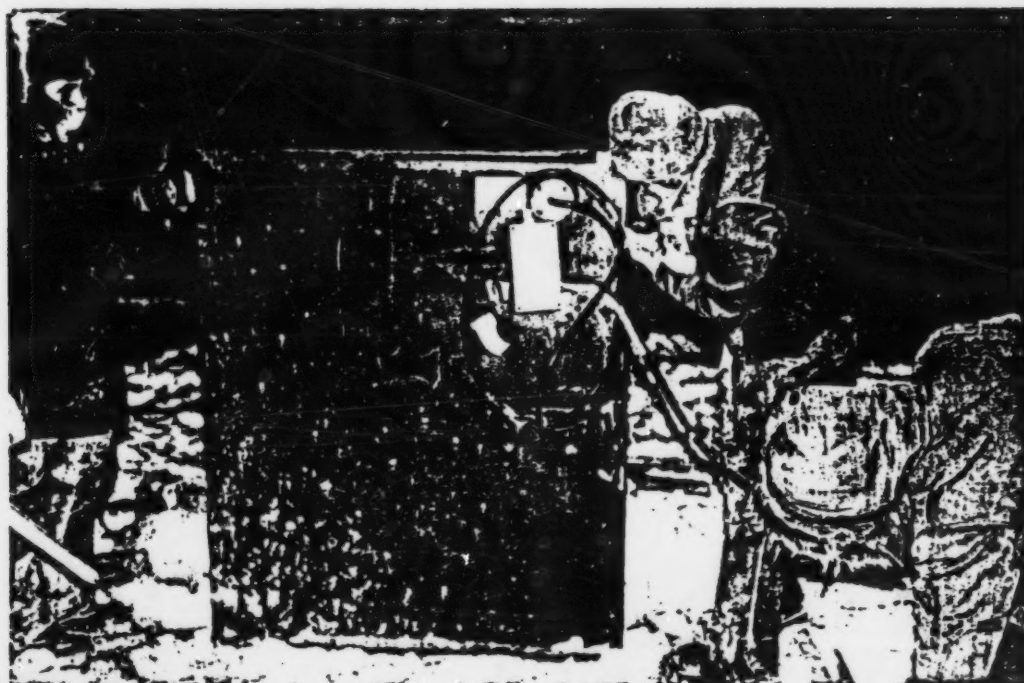


FIGURE 1



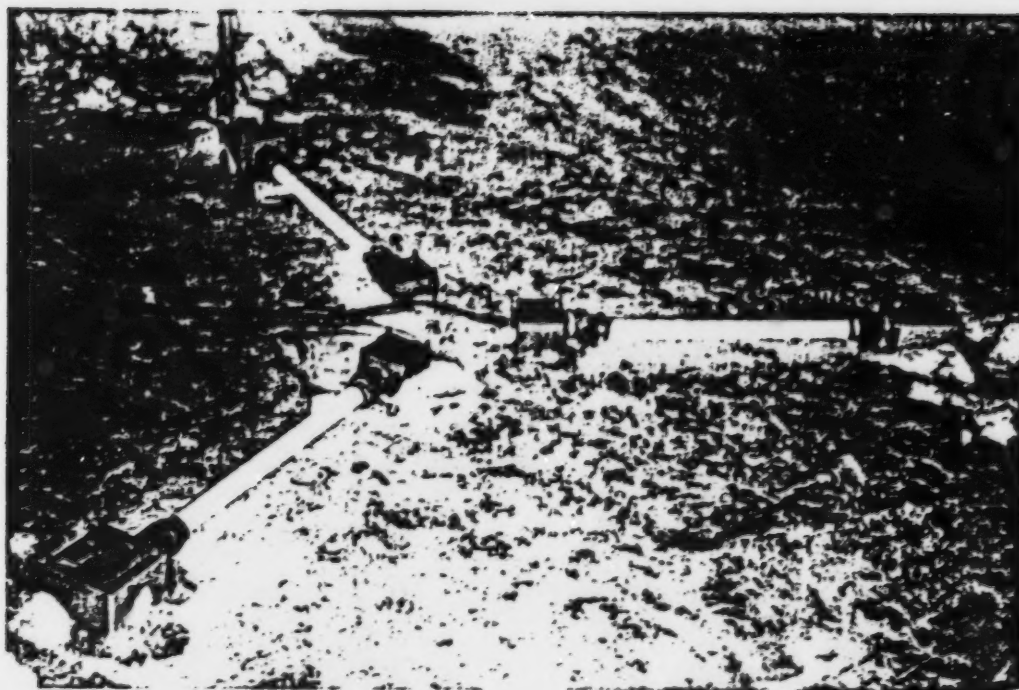
BASIN CONFIGURATION



THE ARCTEC HEXPACK PANEL



THE CMEL MARK IV- C SENSORS



THE INSTRUMAR STRAIN METER ARRAY

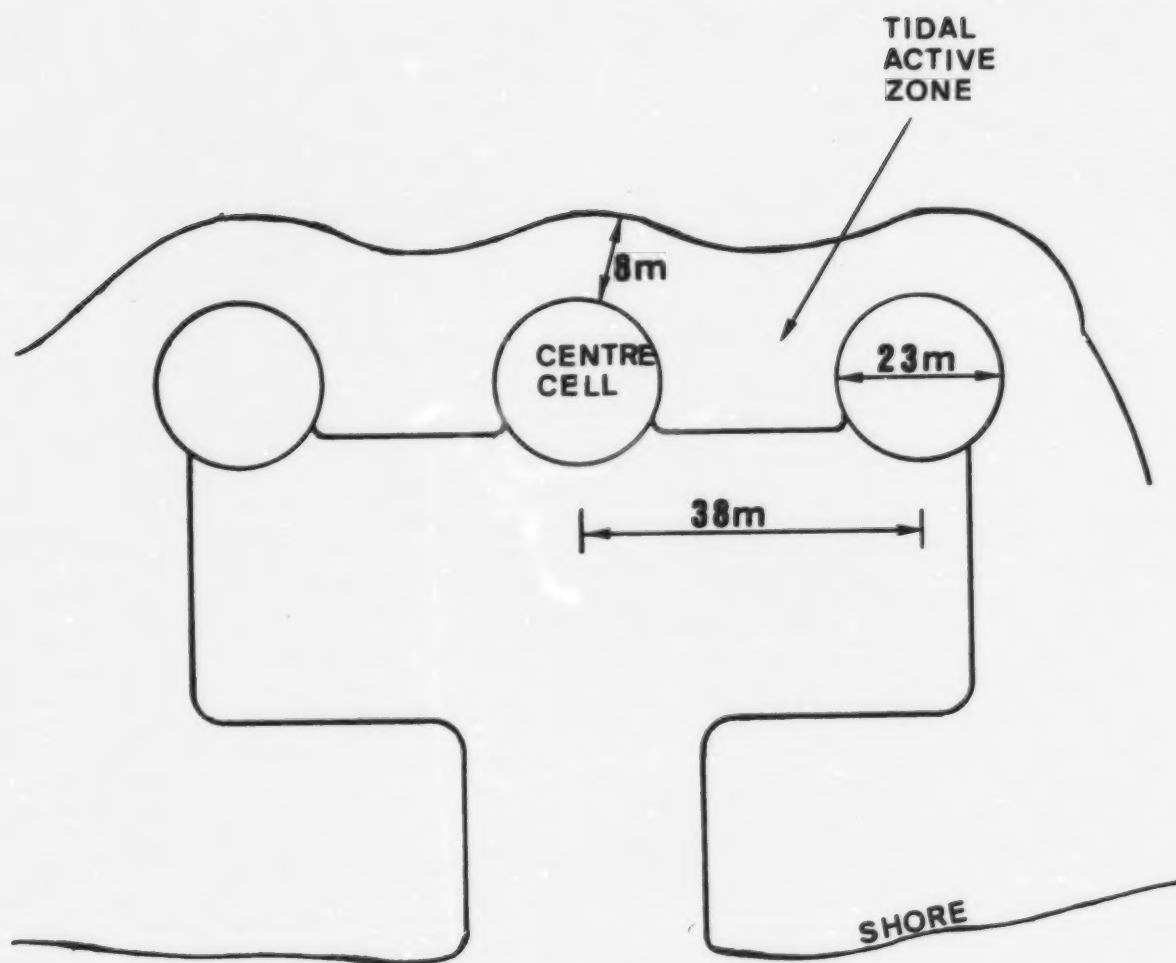


THE MEDOF 1X2m PANEL



THE WEIR-JONES LX1m IDEAL PANEL

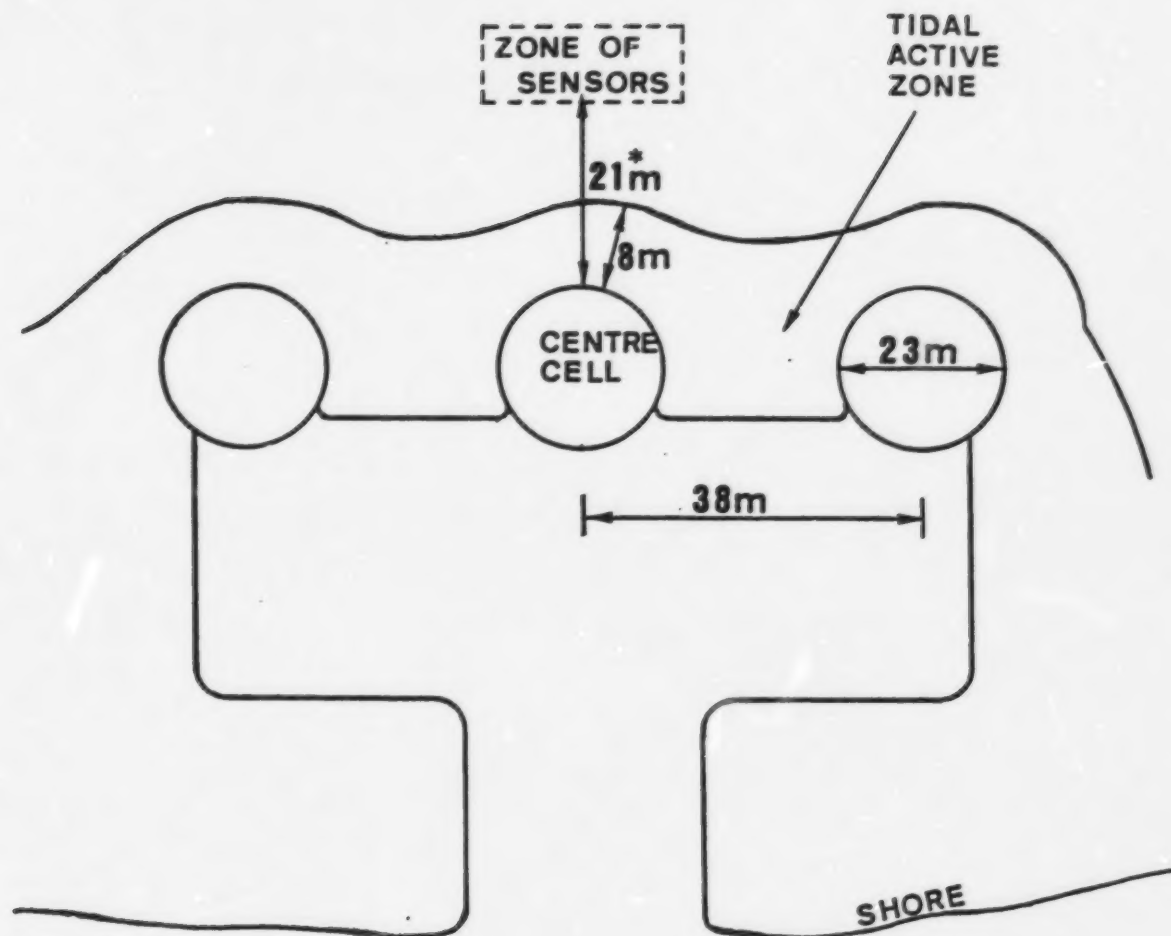
STRATHCONA
SOUND



LAYOUT OF NANISIVIK DOCK

FIGURE 8

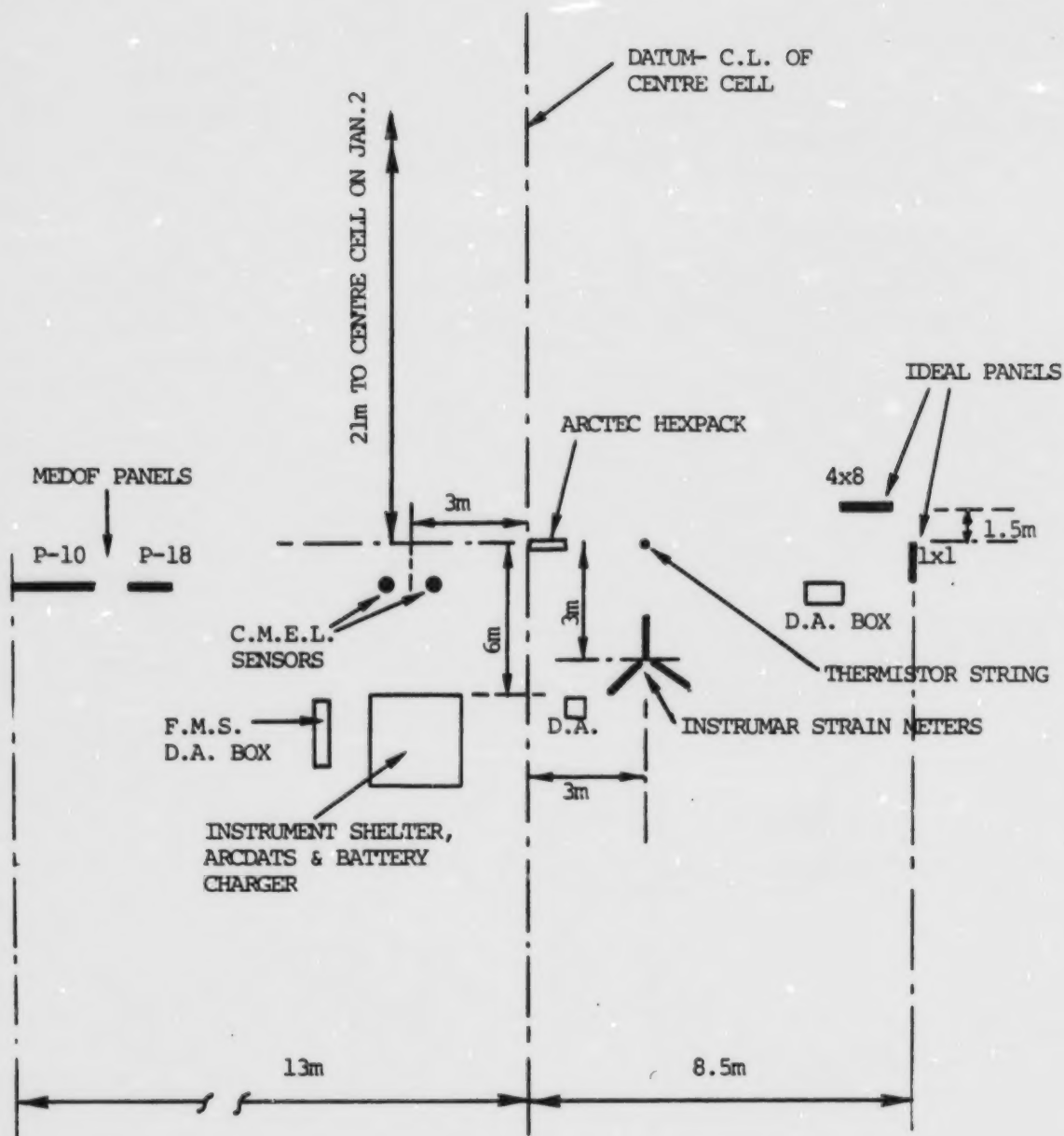
STRATHCONA
SOUND



* INCREASED TO 23.5m JAN. TO MAR.

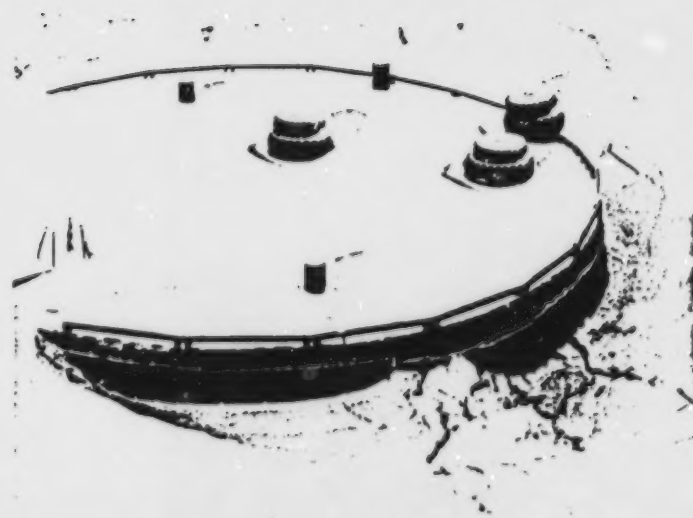
SENSOR LOCATION AREA

FIGURE 9



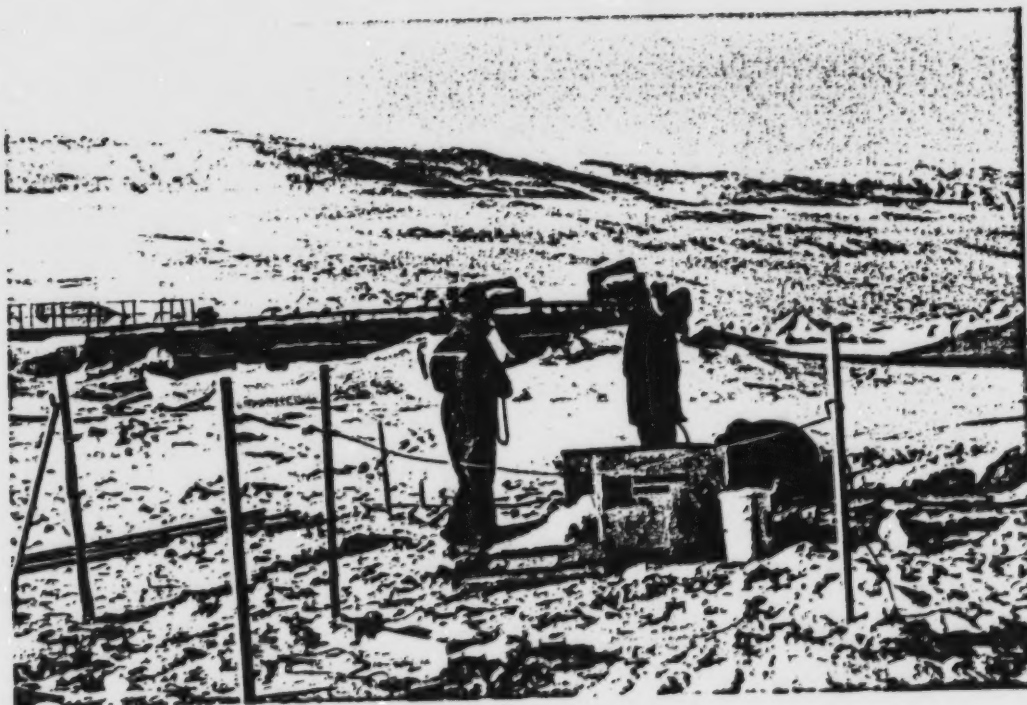
RELATIVE POSITIONS OF SENSORS

FIGURE 10



GENERAL VIEW OF
NANISIVIK DOCK

FIGURE 11



THE SENSOR LOCATION AREA

FIGURE 12



SNOW CLEARING

FIGURE 13



SLOT CUTTING

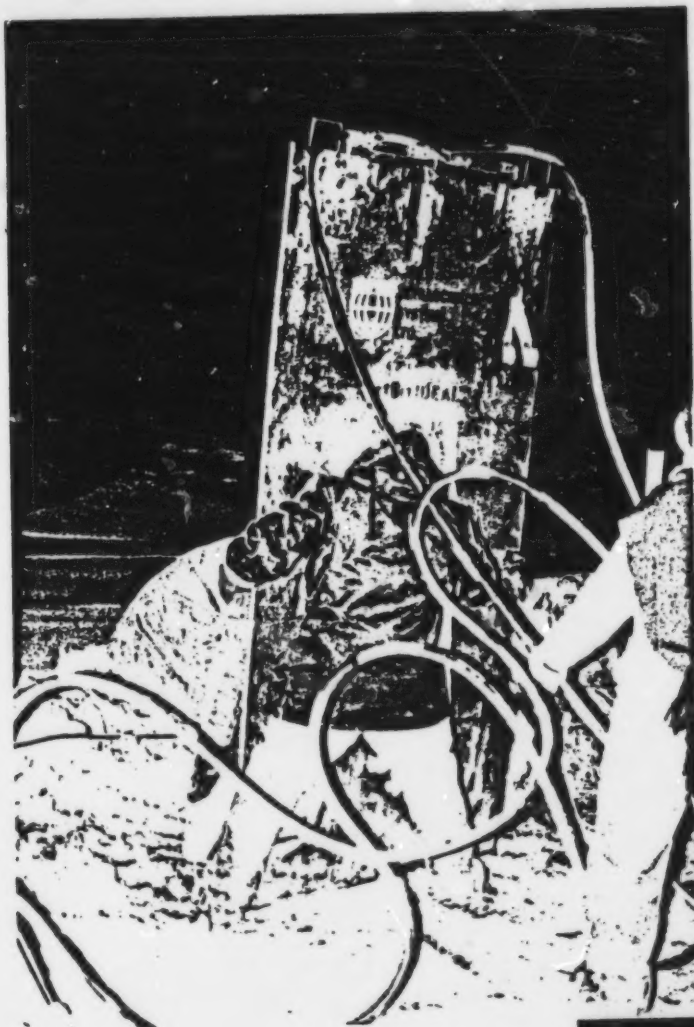
FIGURE 14



FIGURE 15

INSTALLING AN IDEAL
4 X 8 PANEL

FIGURE 16



INSTALLING A 1 X 2m MEDOF
PANEL

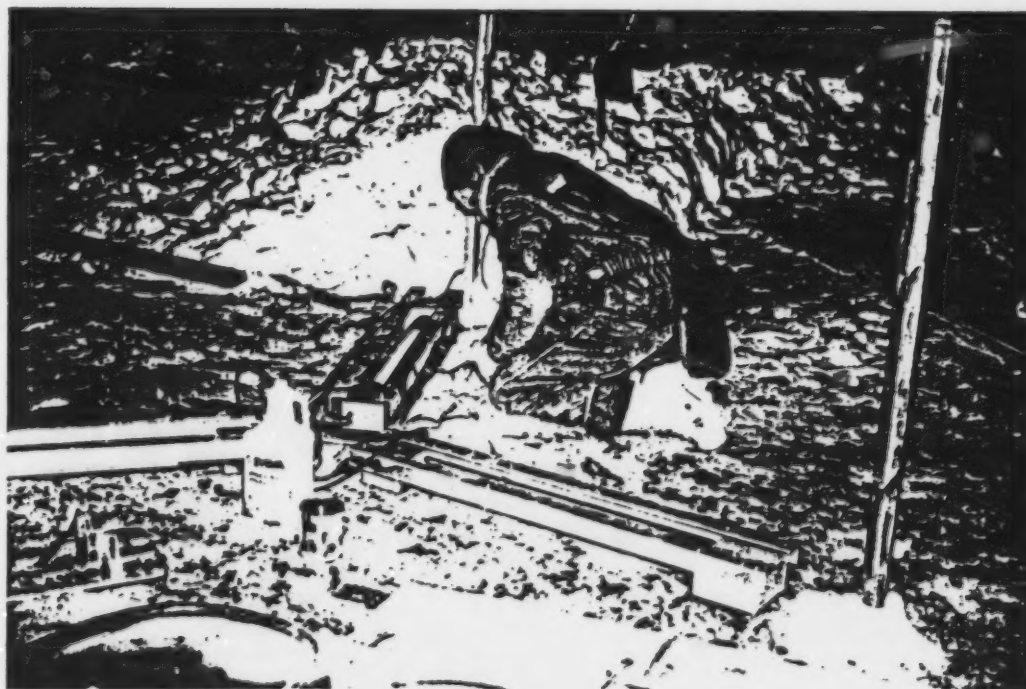
FIGURE 17





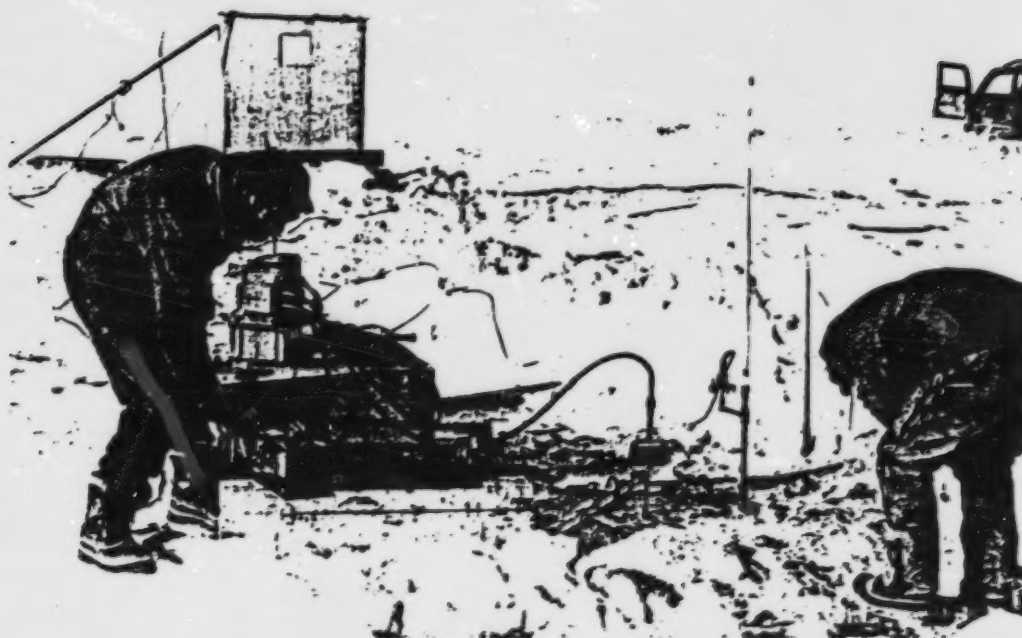
INSTALLING THE CMEL MARK IV-C SENSORS

FIGURE 18

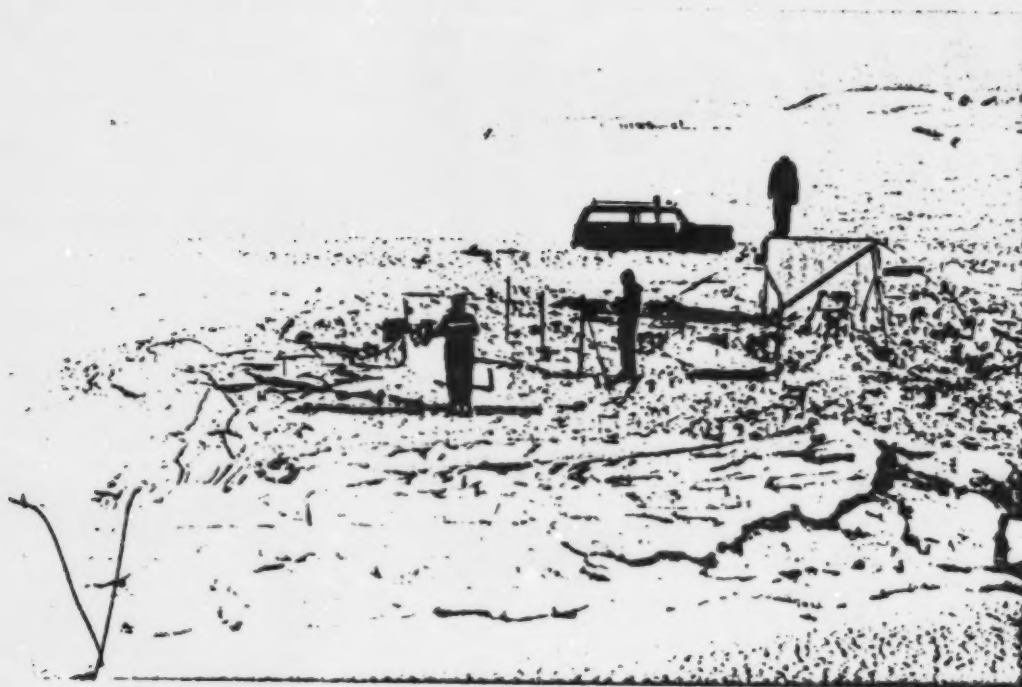


INSTALLING THE INSTRUMAR STRAIN METERS

FIGURE 19



SENSOR CALIBRATION



GENERAL VIEWS OF SITE IN MARCH 1984



SENSOR CALIBRATION

FIGURE 24



SENSOR REMOVAL

FIGURE 25



WEIR-JONES
ENGINEERING
CONSULTANTS
CALGARY

NANISIVIK IFP PROGRAM 1984

NANISIVIK
START TIME
MM/DD/HH:MM
2 / 14 / 13 / 49

CHANNEL 0 1M*1M KPA

CHANNEL 1 4*8 PANEL SUMMATION KPA

MM/DD 0 100 200 300 400 500 600 700 800 900

2 / 14 + + + + + + + + + +

1 X 1

4 X 8

2 / 15 + + + + + + + + + +

2 / 16 + + + + + + + + + +

2 / 17 + + + + + + + + + +

"IDEAL" PANEL OUTPUTS (SUMMATION)

FIGURE 26



WEIR-JONES
ENGINEERING
CONSULTANTS
CALGARY

NANISIVIK IFP PROGRAM 1984

NANISIVIK
START TIME
MM/DD/HH:MM
2 / 14 / 13 / 49

CHANNEL 4 SENSOR 2A KPA

CHANNEL 5 SENSOR 2B KPA

MM/DD 0 100 200 300 400 500 600 700 800 900

2 / 14

+

+

+

+

+

+

+

+

+

+

+

2A

2B

2 / 15

+

+

+

+

+

+

+

+

+

+

+

2 / 16

+

+

+

+

+

+

+

+

+

+

+

2 / 17

+

+

+

+

+

+

+

+

+

+

+

4 X 8 "IDEAL" PANEL
INDIVIDUAL CHANNEL OUTPUTS

FIGURE 27

4 X 8 "IDEAL" PANEL 16 HOUR AVERAGES

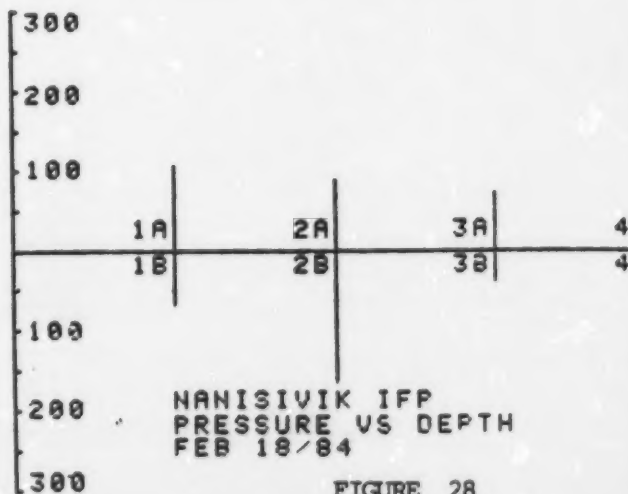
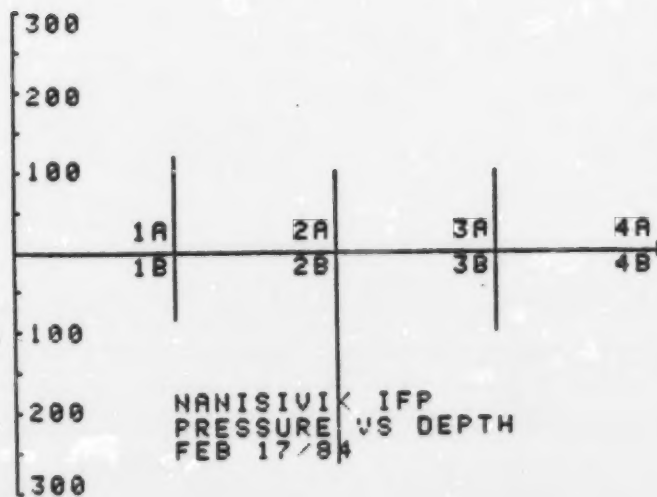
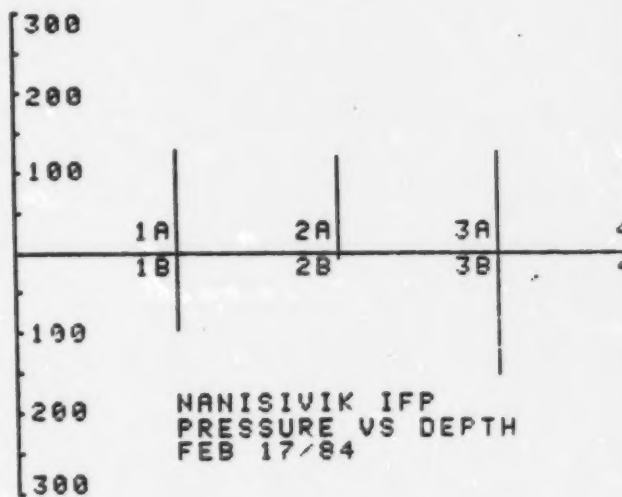
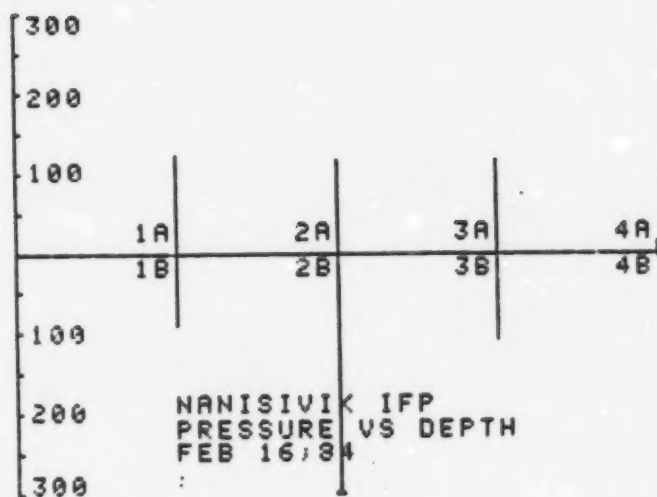
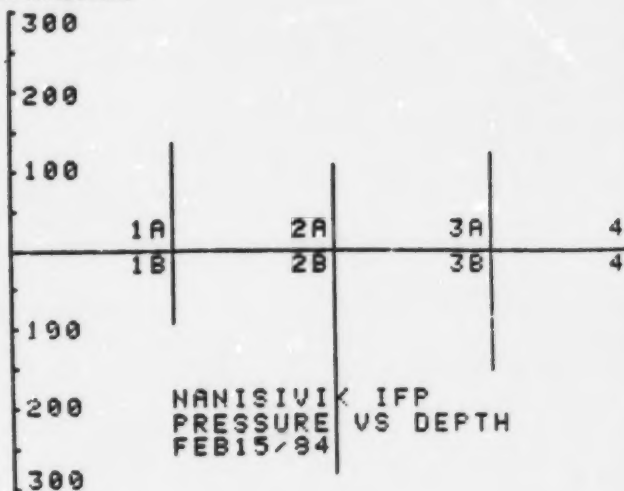
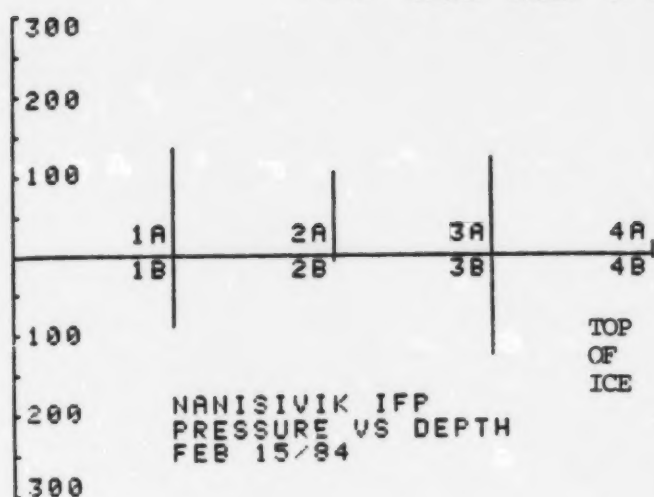


FIGURE 28

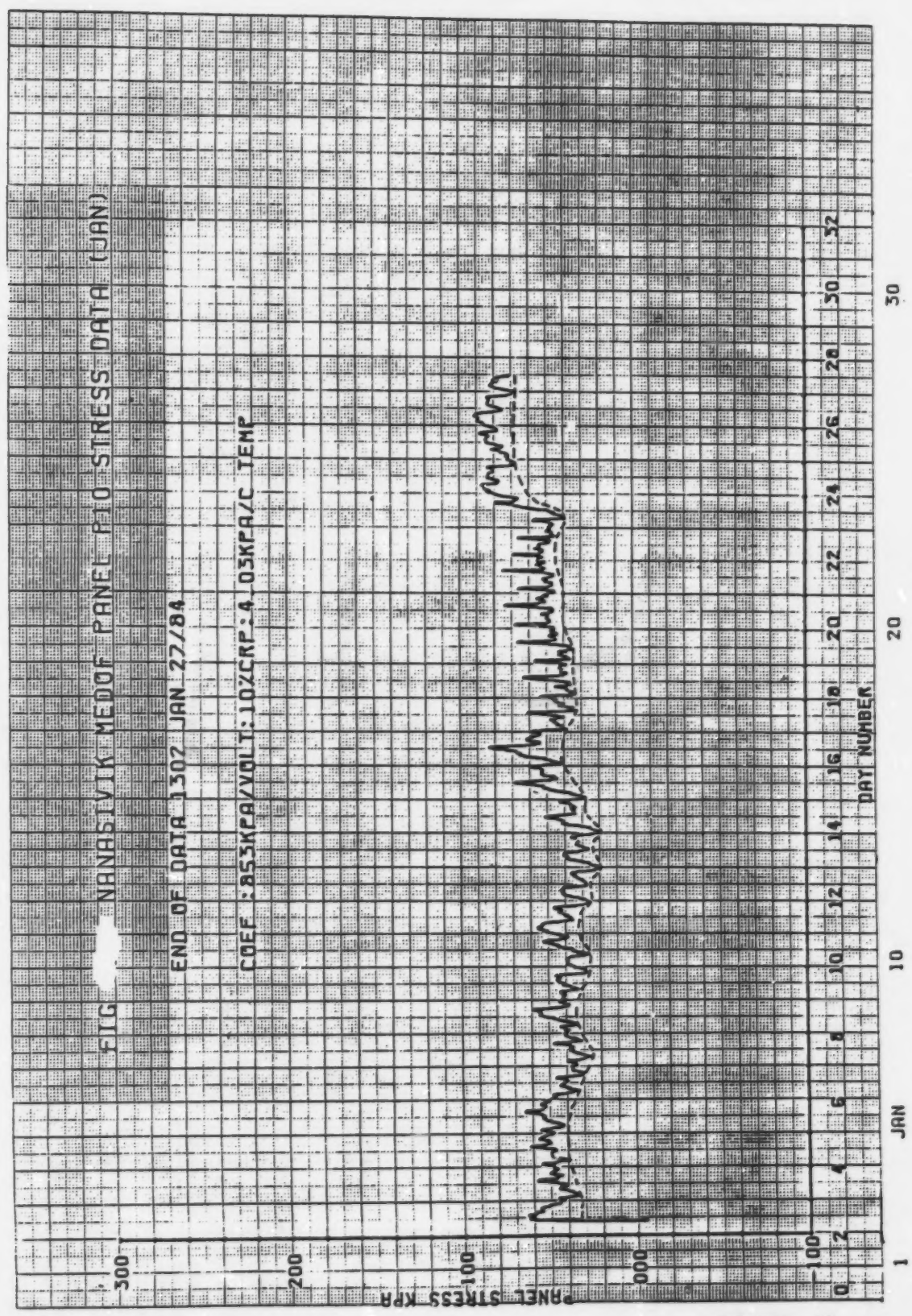


FIGURE 29

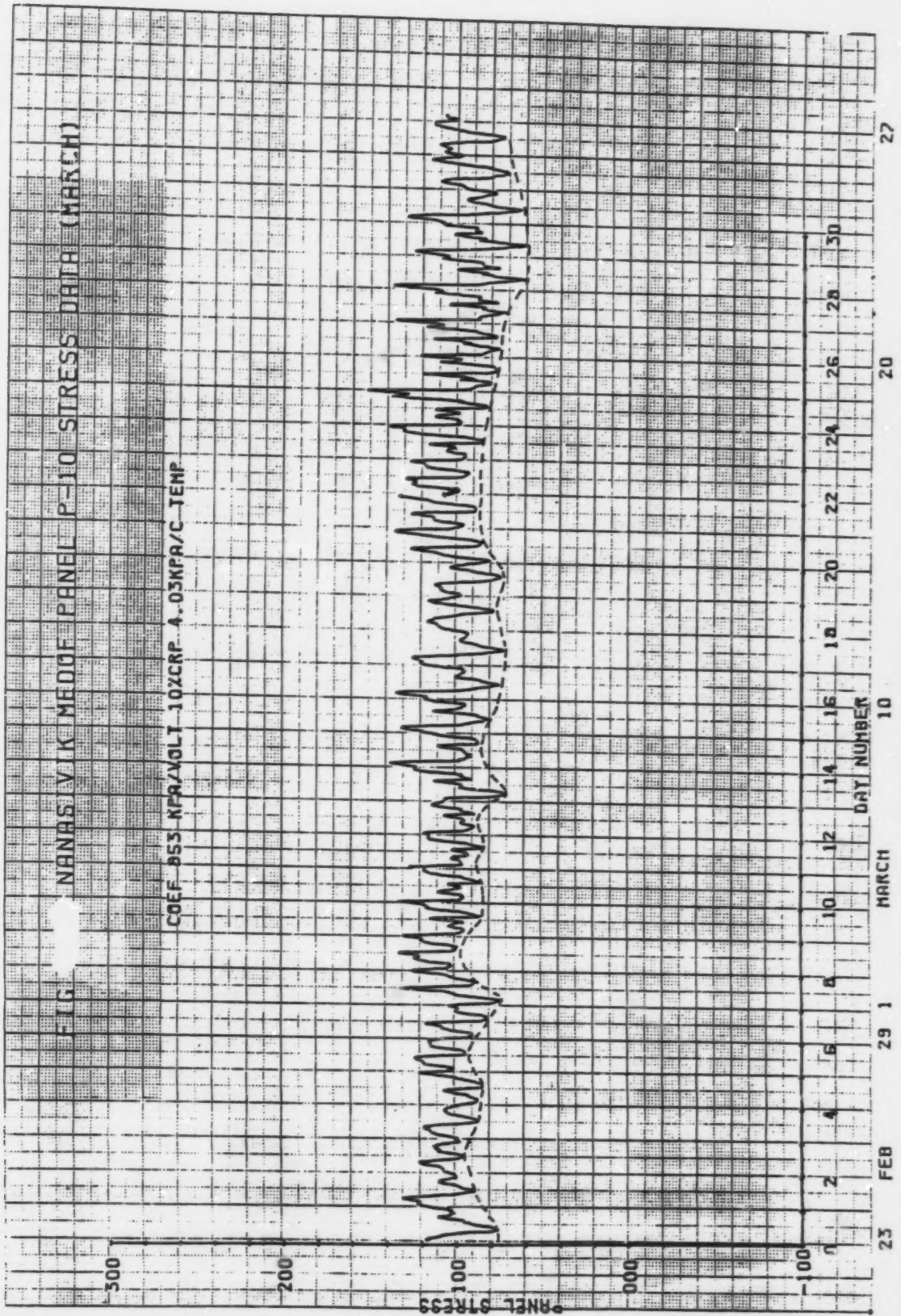


FIGURE 30

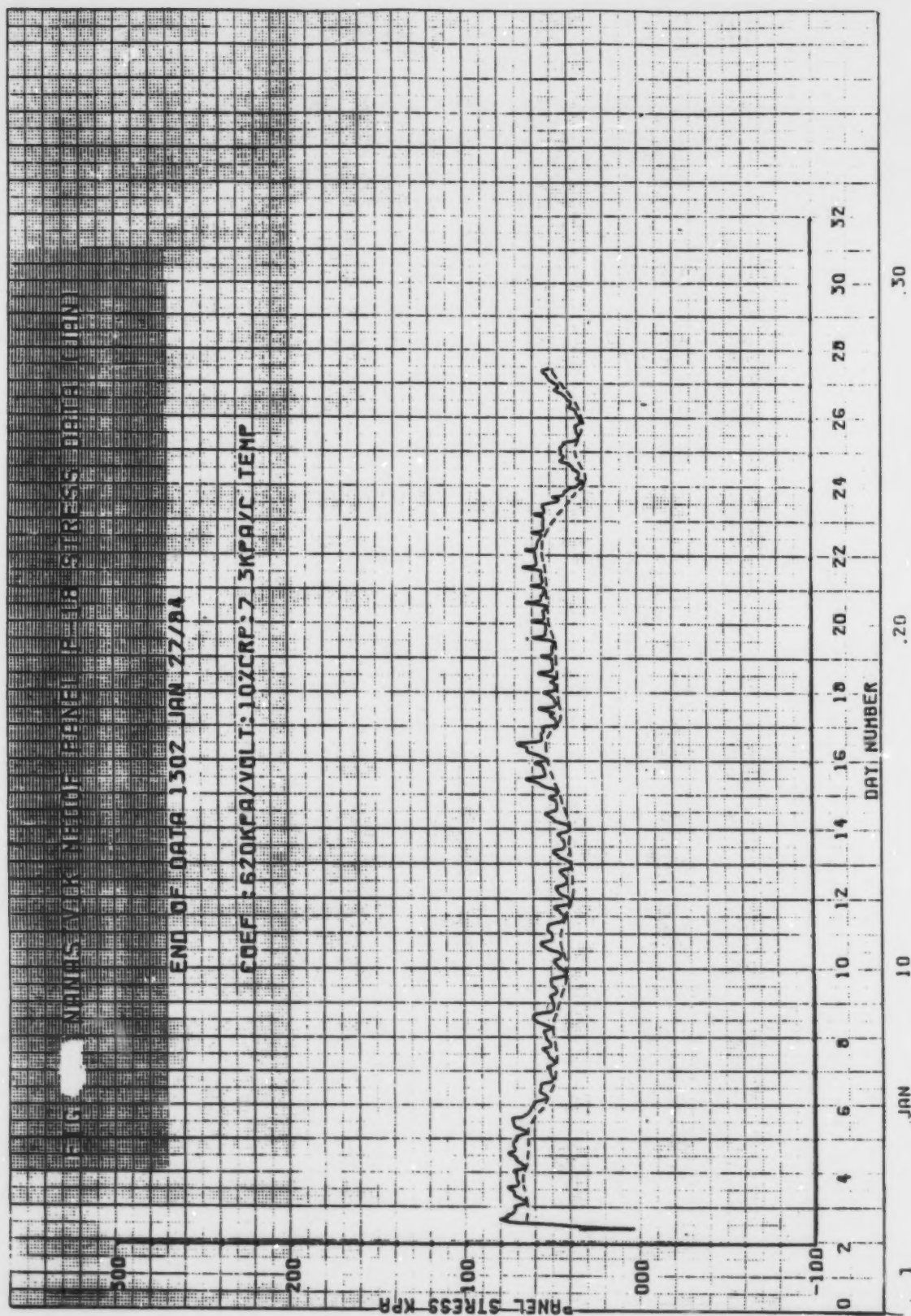


FIGURE 31

ARCTEC HEXPACK

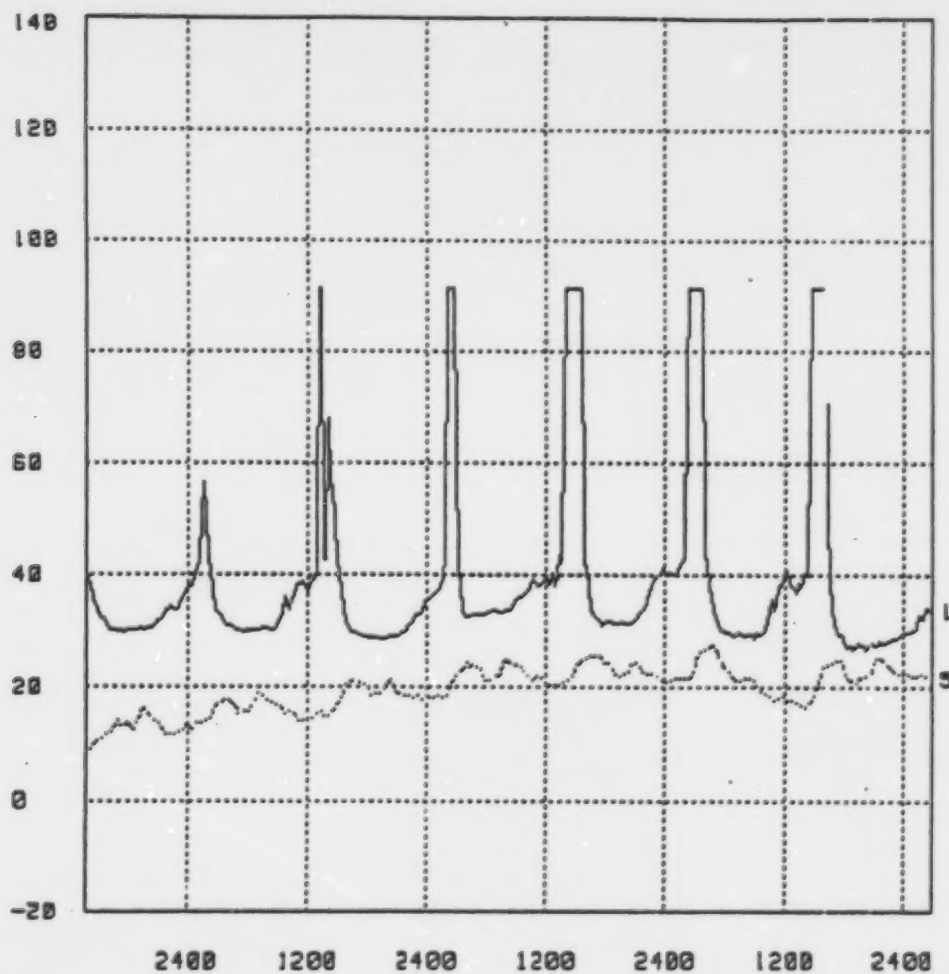
TYPICAL ICE PRESSURE DATA

DATE	TIME (approx)	TIDE CONDITION	HEX PACK STRIP PRESSURES kPa				ESTIMATED AVERAGE kPa
			TOP #1	#5	BOTTOM #3	#6	
03/1	1300	HIGH	120	20	15	30	46
03/1	1740	LOW	30	20	1019	335	351
04/1	0220	HIGH	130	20	20	25	49
04/1	0630	LOW	35	20	1014	567	407
06/1	1530	HIGH	110	25	10	0	36
06/1	2000	LOW	25	25	910	598	390
13/1	2200	HIGH	120	25	10	5	40
14/1	0340	LOW	25	25	280	45	94

FIGURE 32

NANISIVIC HEXPACK DATA

PRESSURE (KPA) VS TIME



START DATE (DAY/MONTH) =2/1
START TIME =13:52
ENDING DATE (DAY/MONTH)=6/1
ENDING TIME =2:52

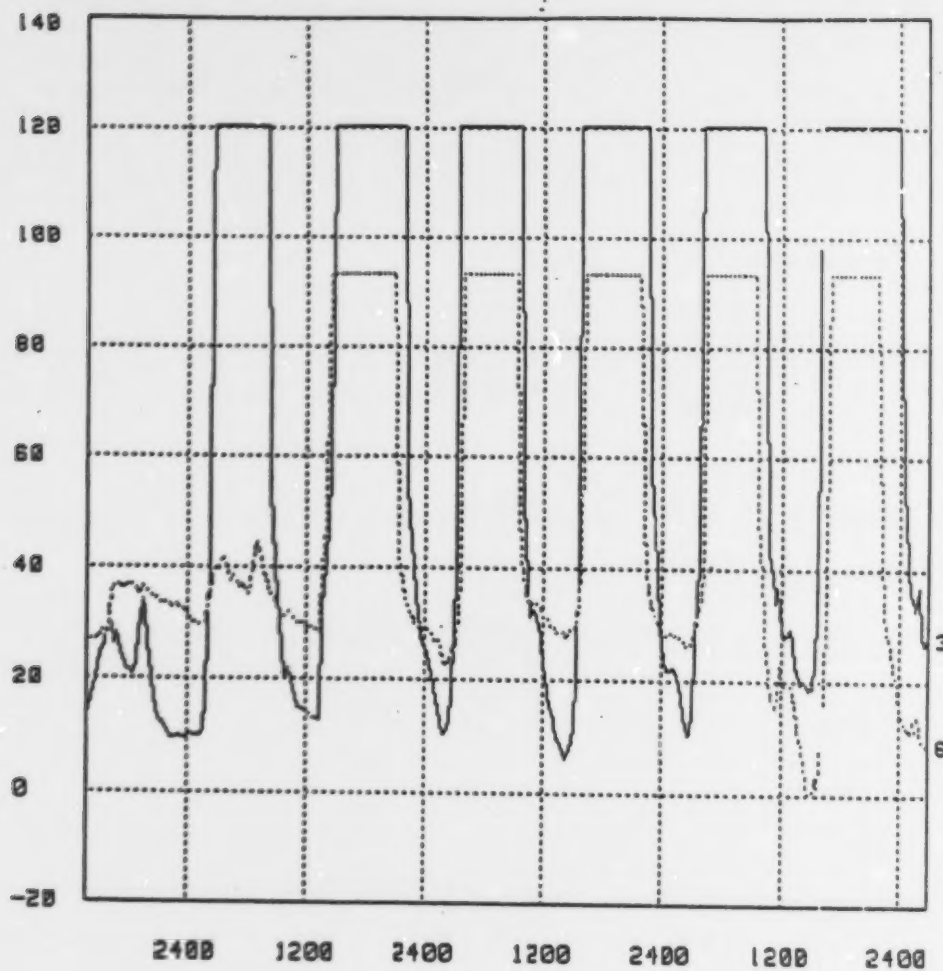
NANO HEXPACK STRIPS

1
5

FIGURE 33

NANISIVIC HEXPACK DATA

PRESSURE (KPA) VS TIME



START DATE (DAY/MONTH) =2/1
 START TIME =13:52
 ENDING DATE (DAY/MONTH)=6/1
 ENDING TIME =2:52

NANO HEXPACK STRIPS

3
6

FIGURE 34

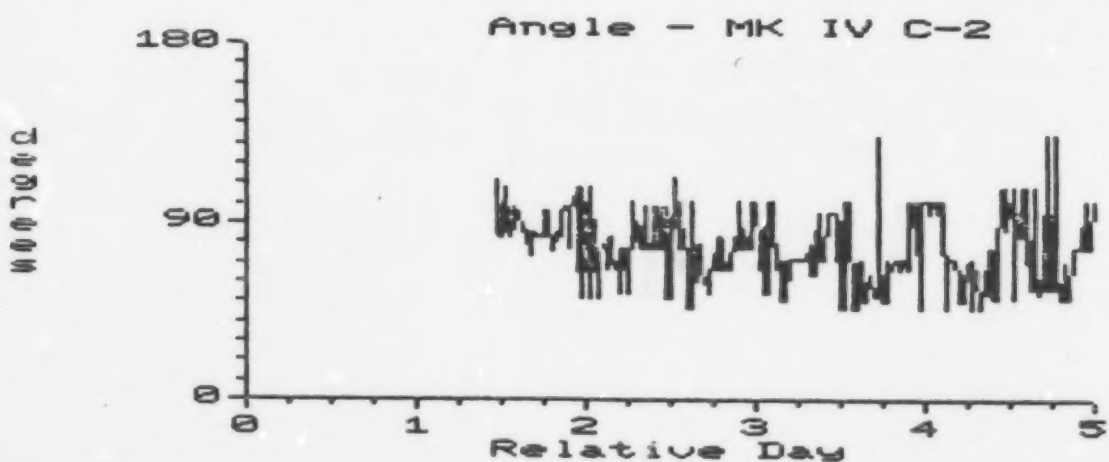
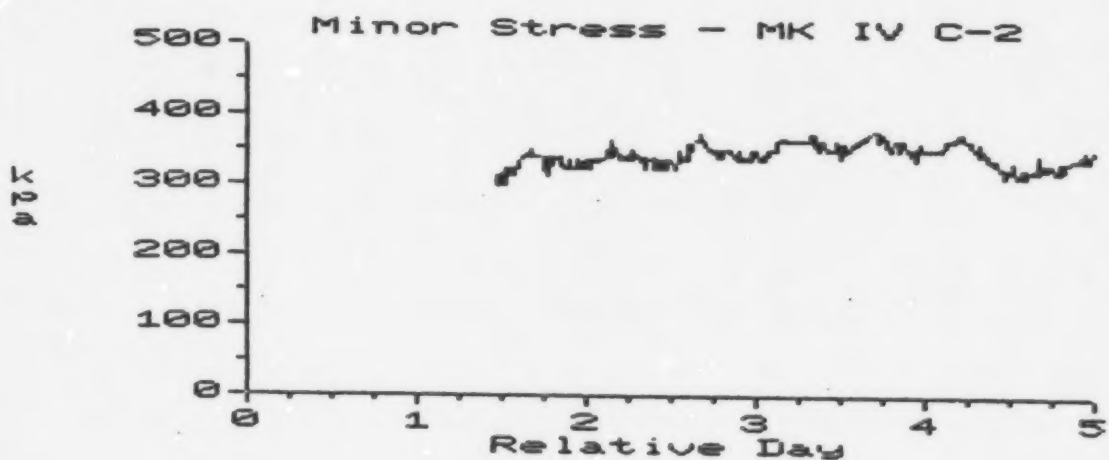
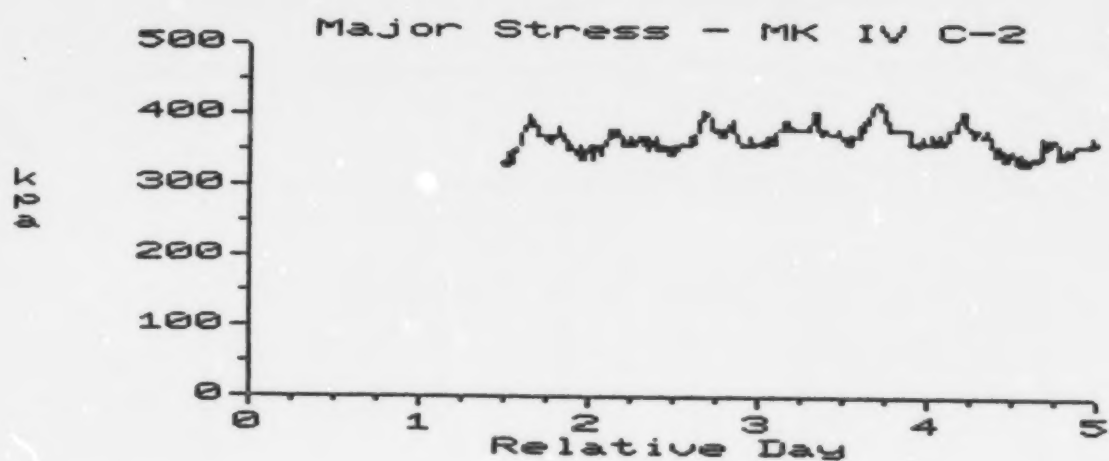


FIGURE 35

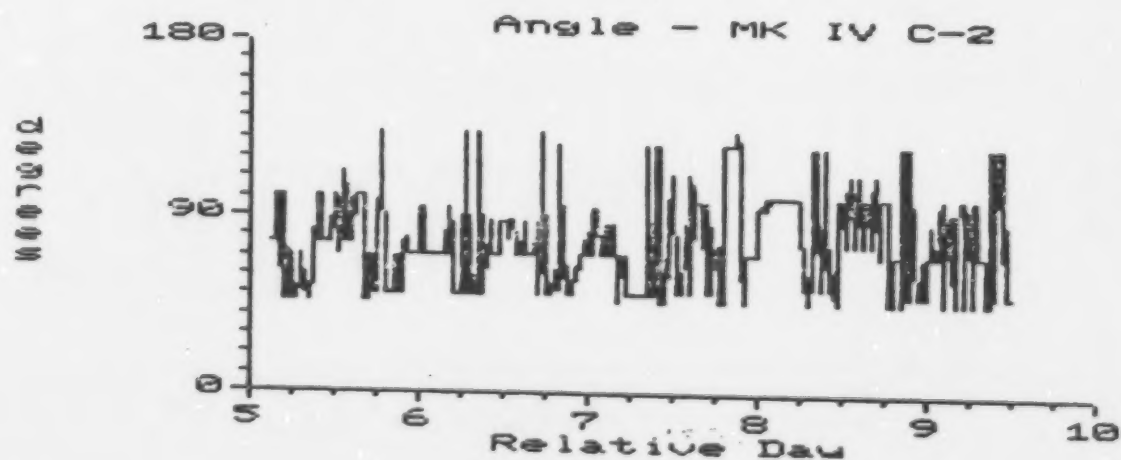
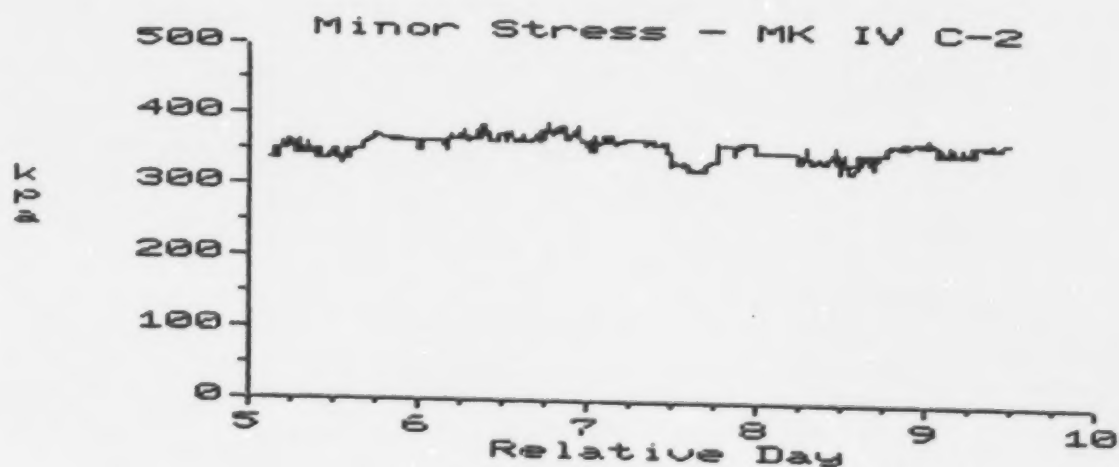
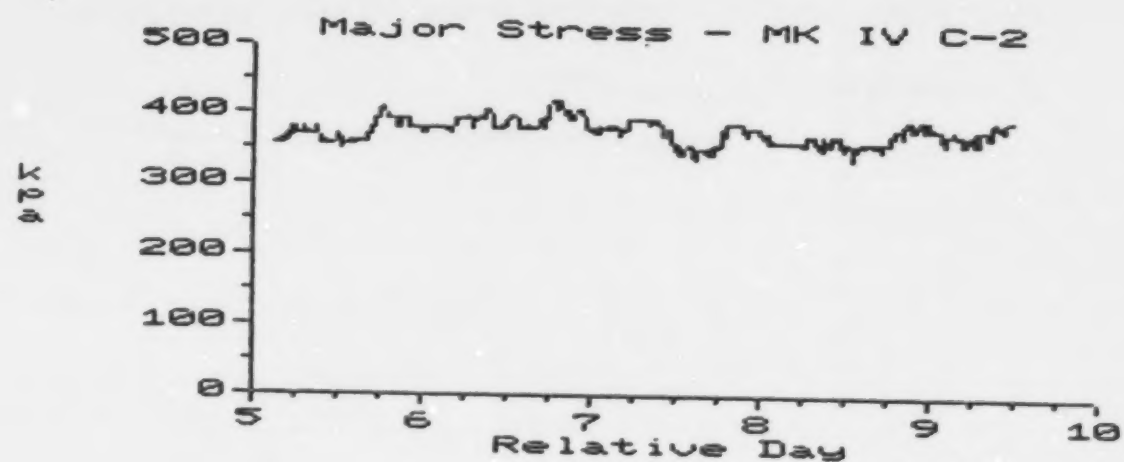


FIGURE 36

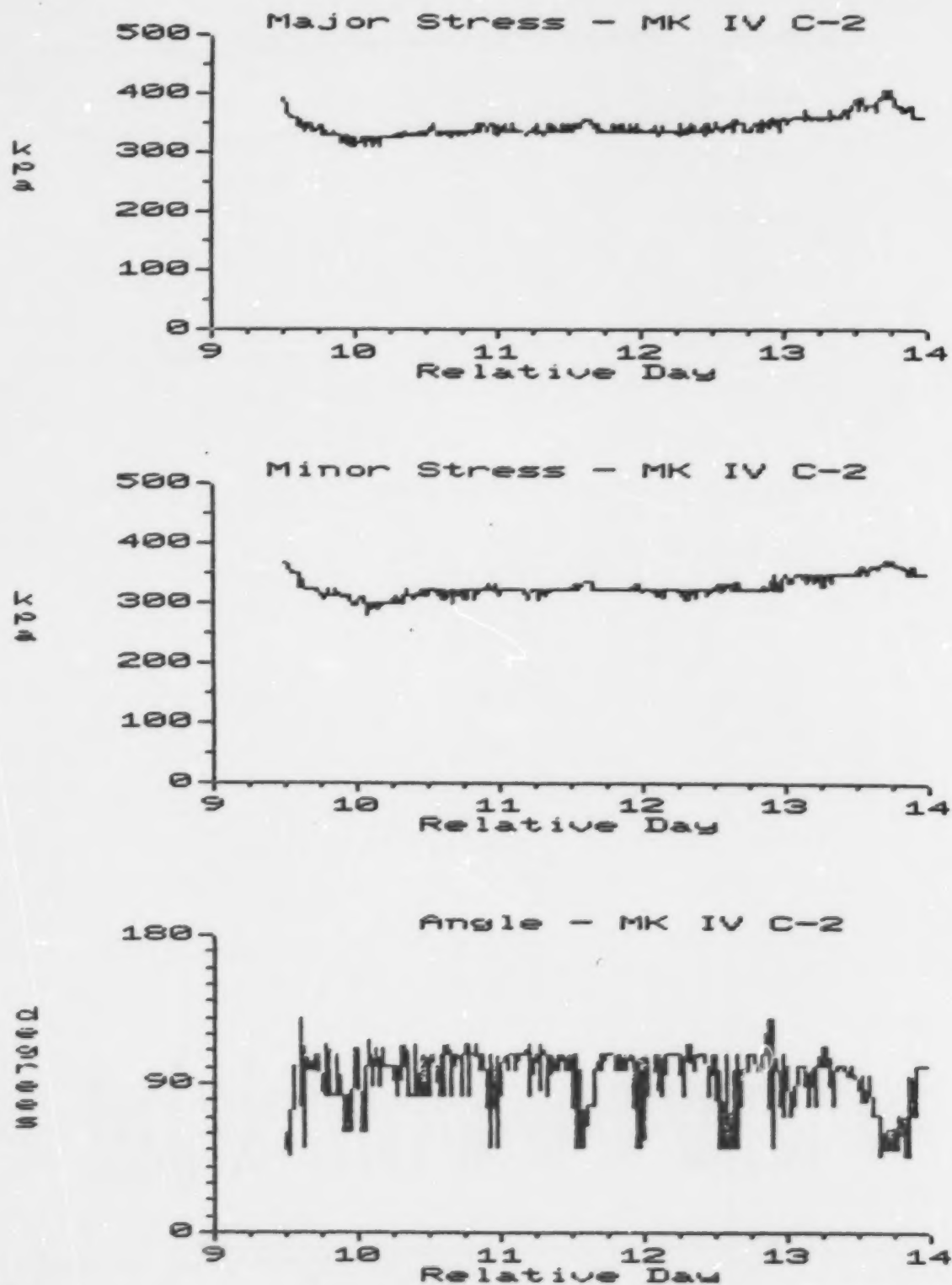


FIGURE 37

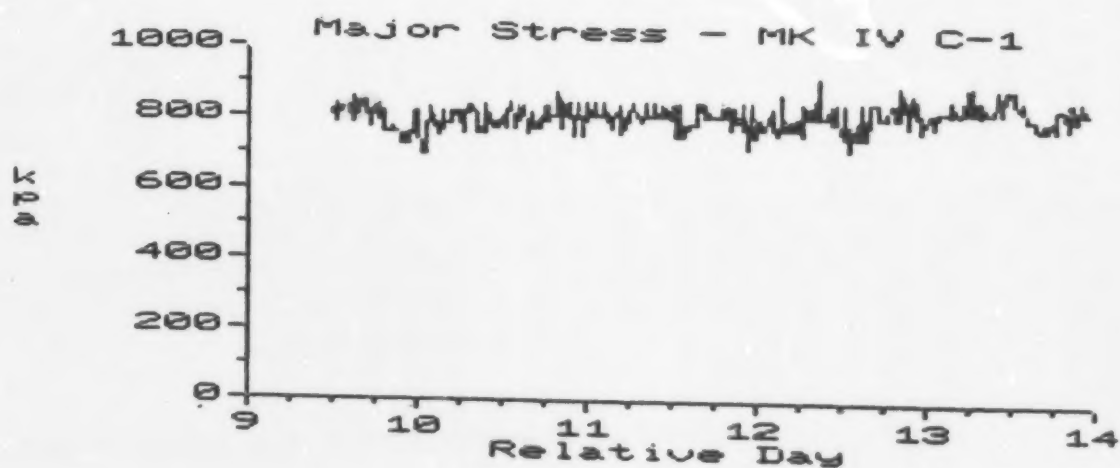
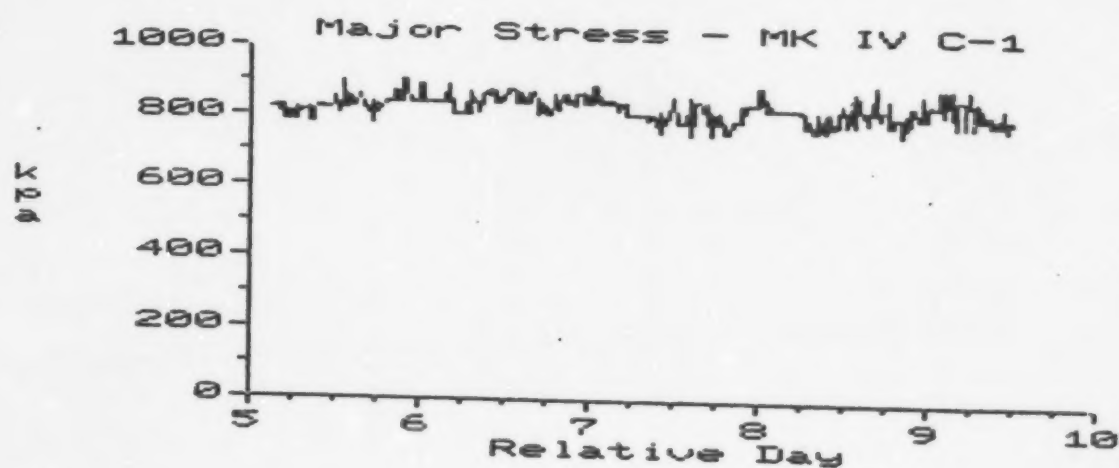
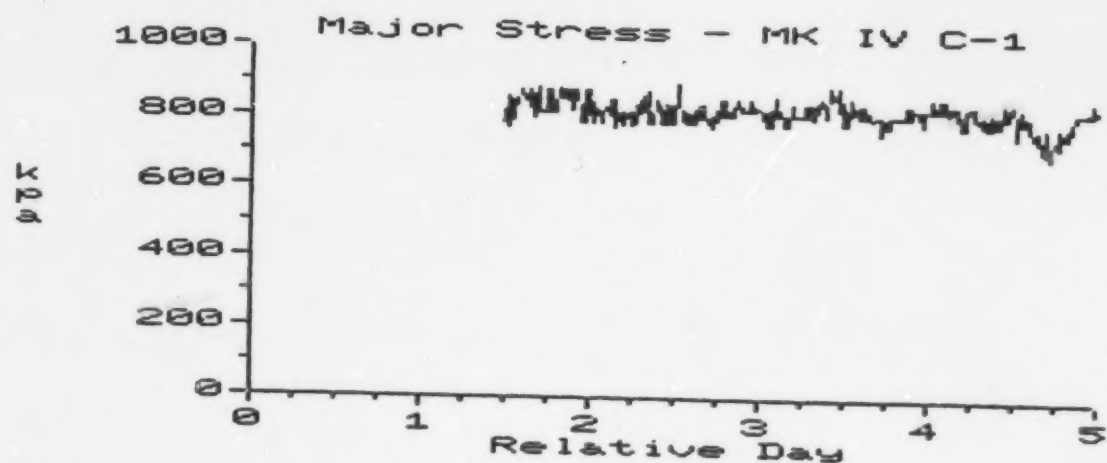
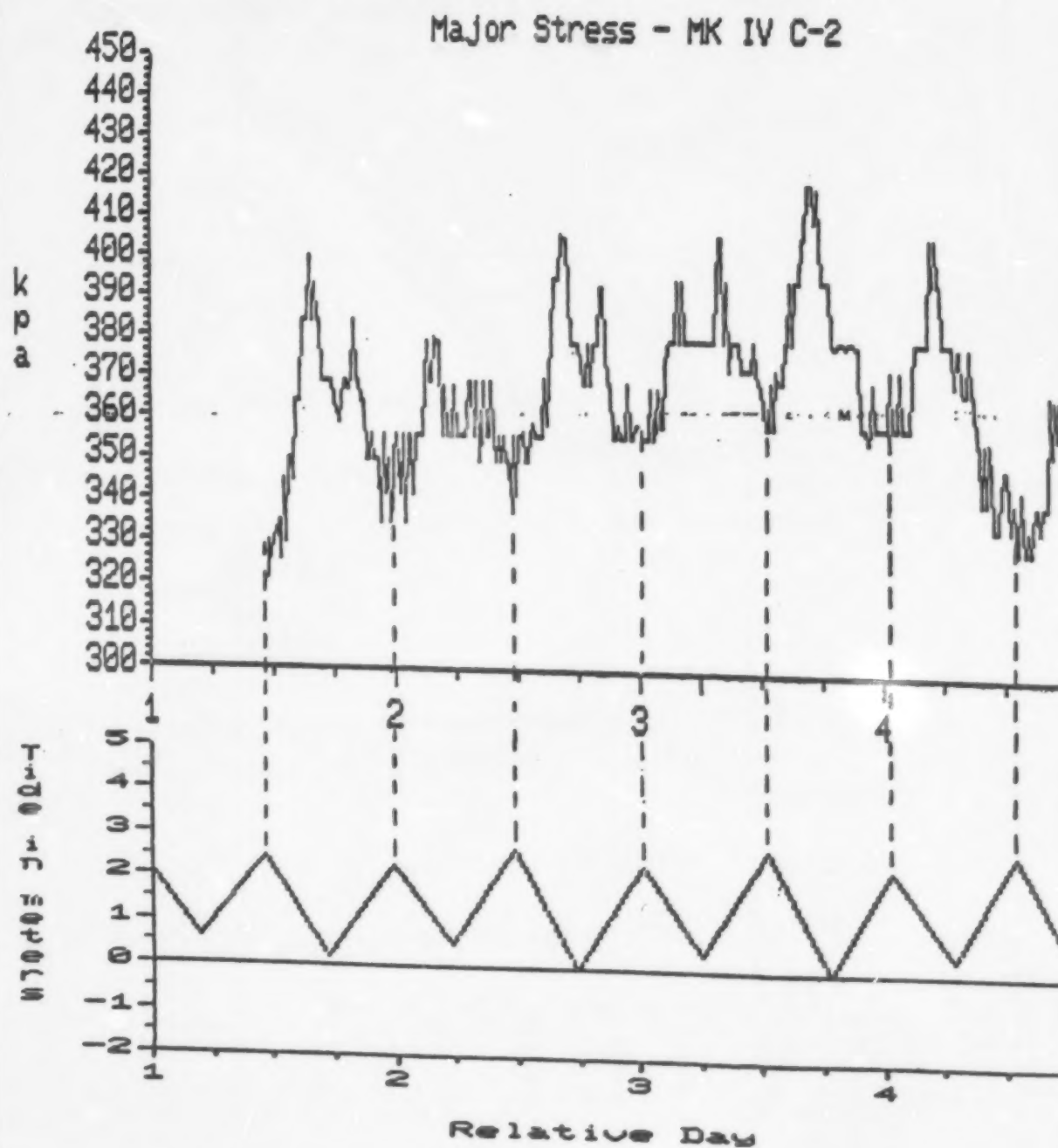
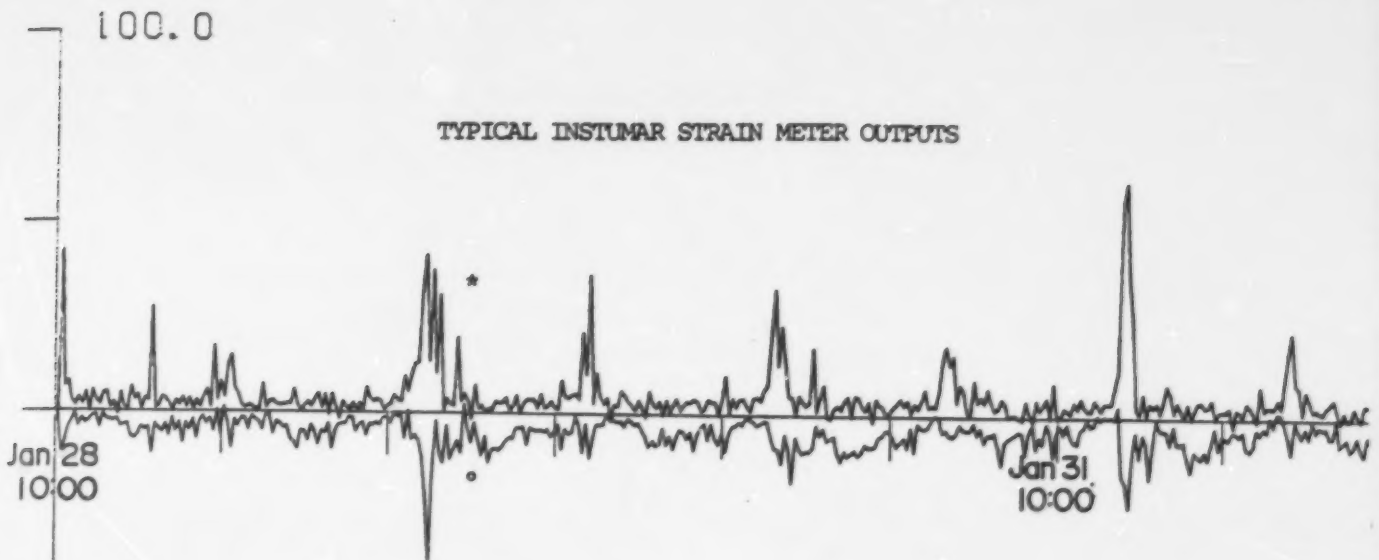


FIGURE 38



COMPARISON OF MAJOR STRESS FOR SENSOR 2 WITH
TIDAL CYCLE



$e_{max} \cdot e_{min}.$

-100.0

Plot of Incremental
Emin, Emax and Angle

X Axis - Time

(marks every 12 hours)

Y Axis (top) Micro-Strains

(marks every 50 $\mu\epsilon$)

Y Axis (bottom) Angle

90

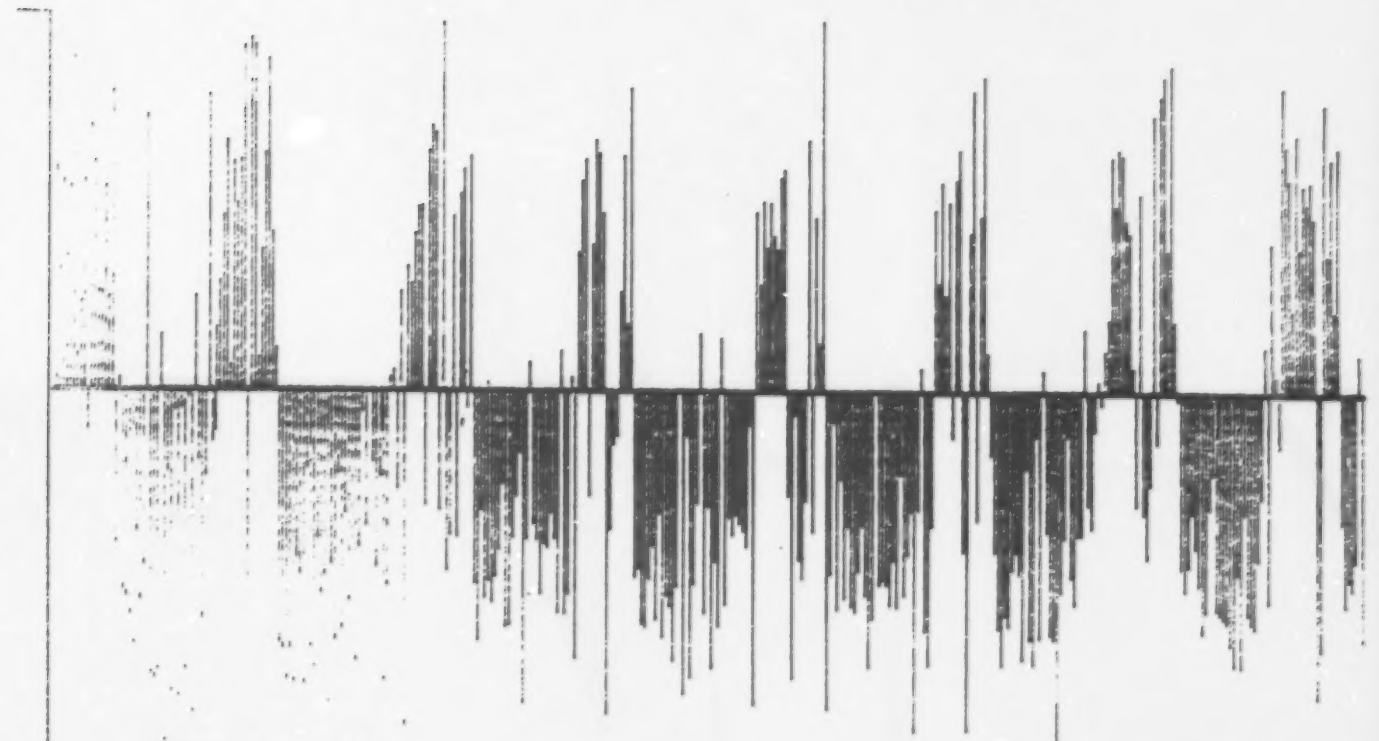


FIGURE 39A

-90

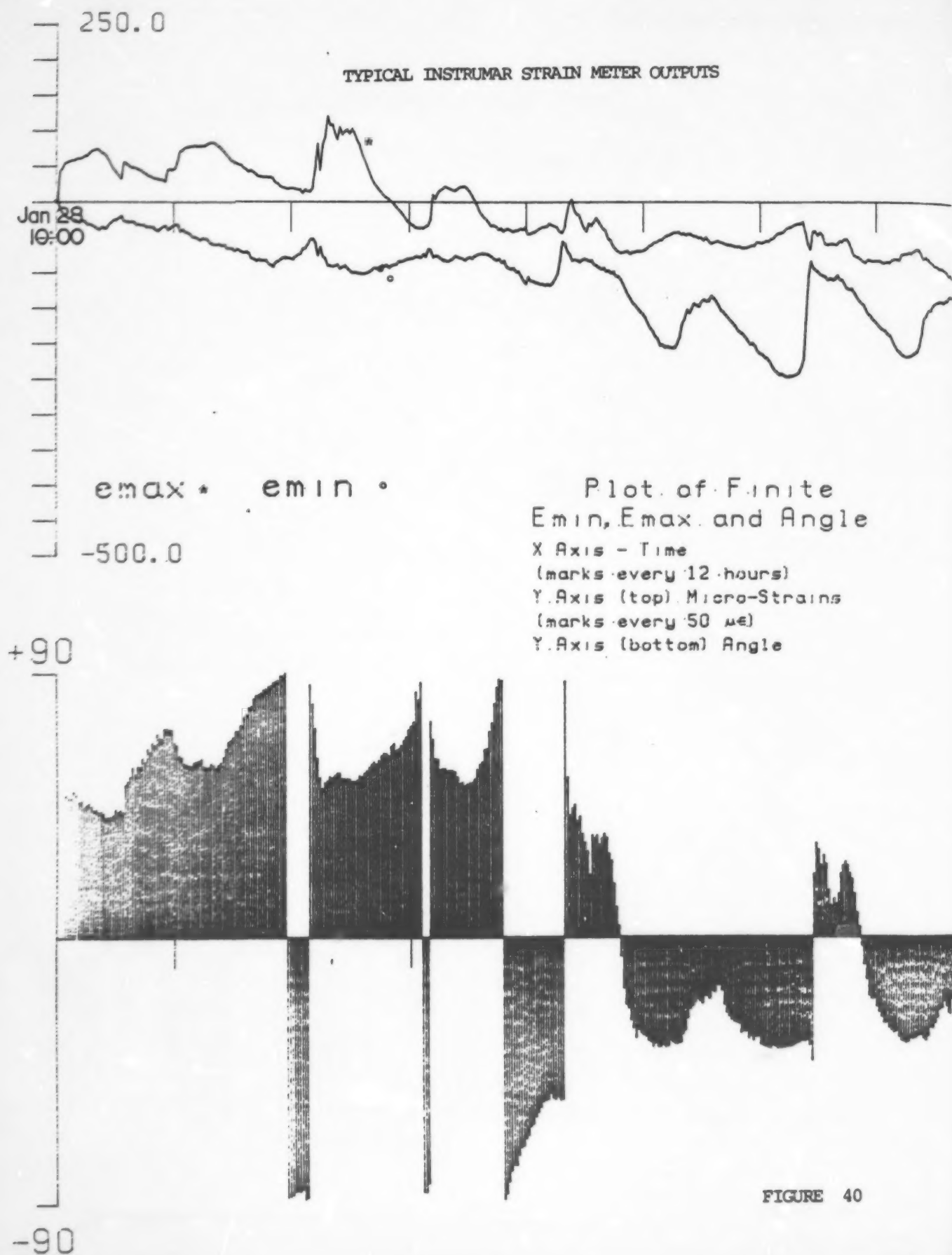


FIGURE 40

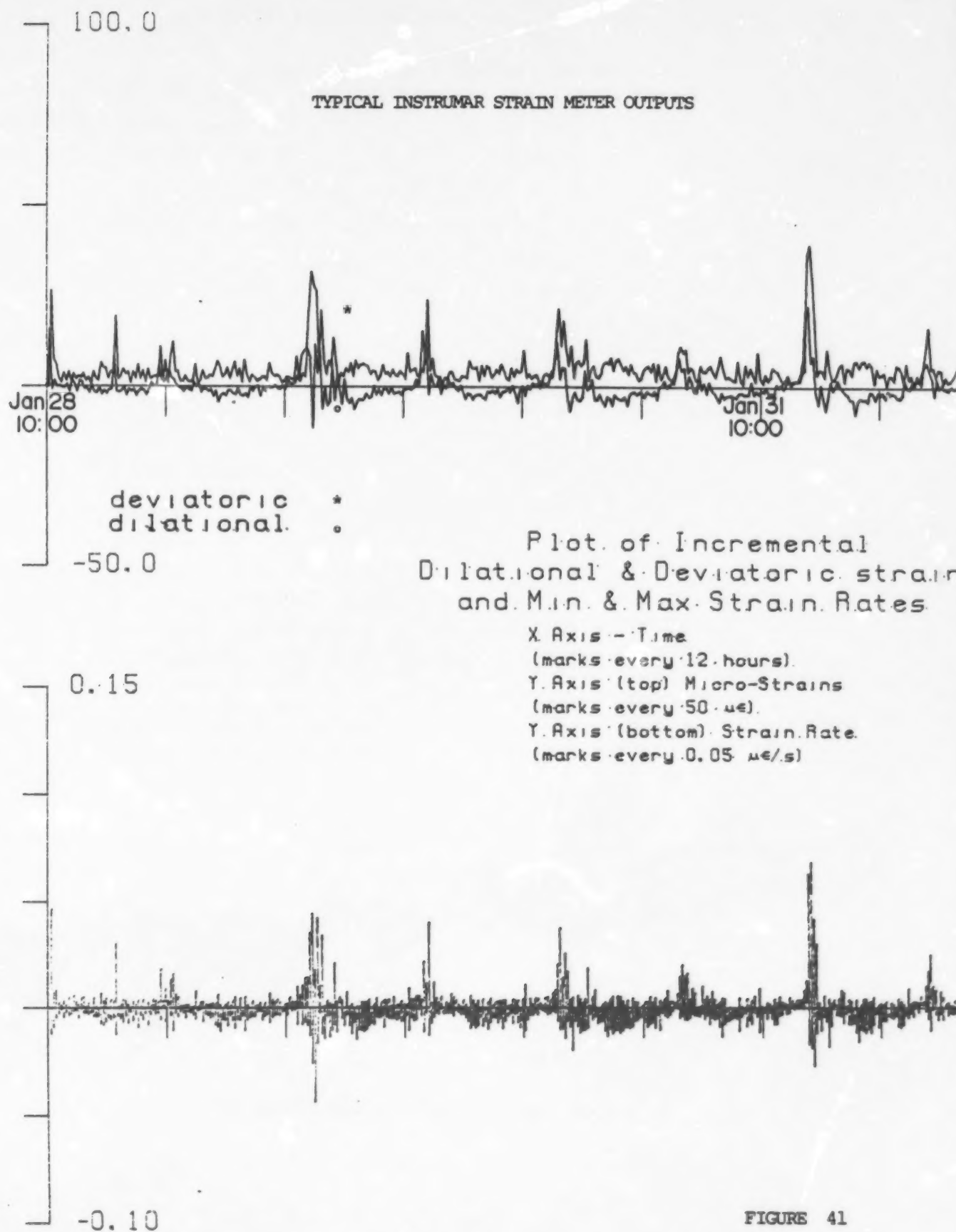
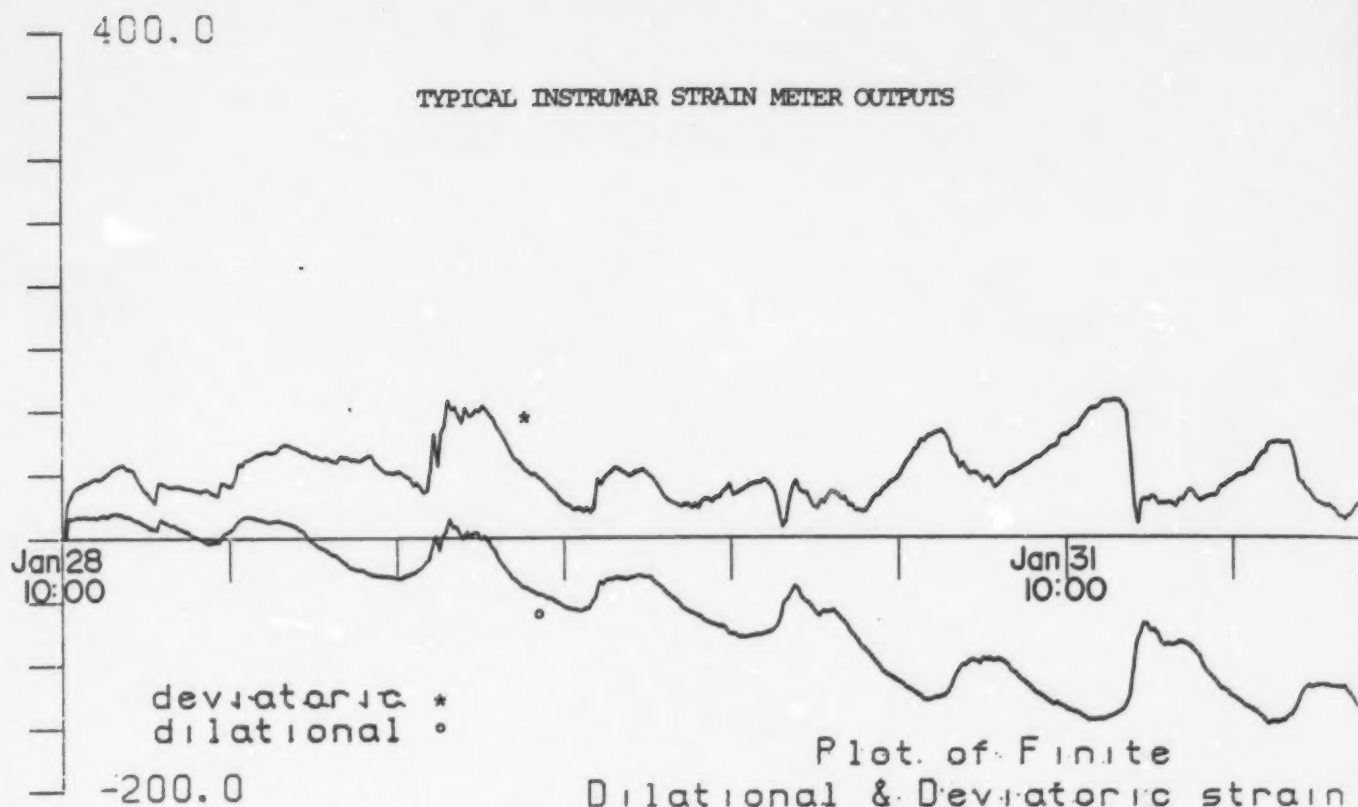


FIGURE 41



Plot of Finite
Dilational & Deviatoric strain
and Min. & Max. Strain Rates

X Axis - Time.

(marks every 12 hours)

Y. Axis (top) Micro-Strains

(marks every 50 $\mu\epsilon$)

Y. Axis (bottom) Strain Rate.

(marks every 0.05 $\mu\epsilon/s$)

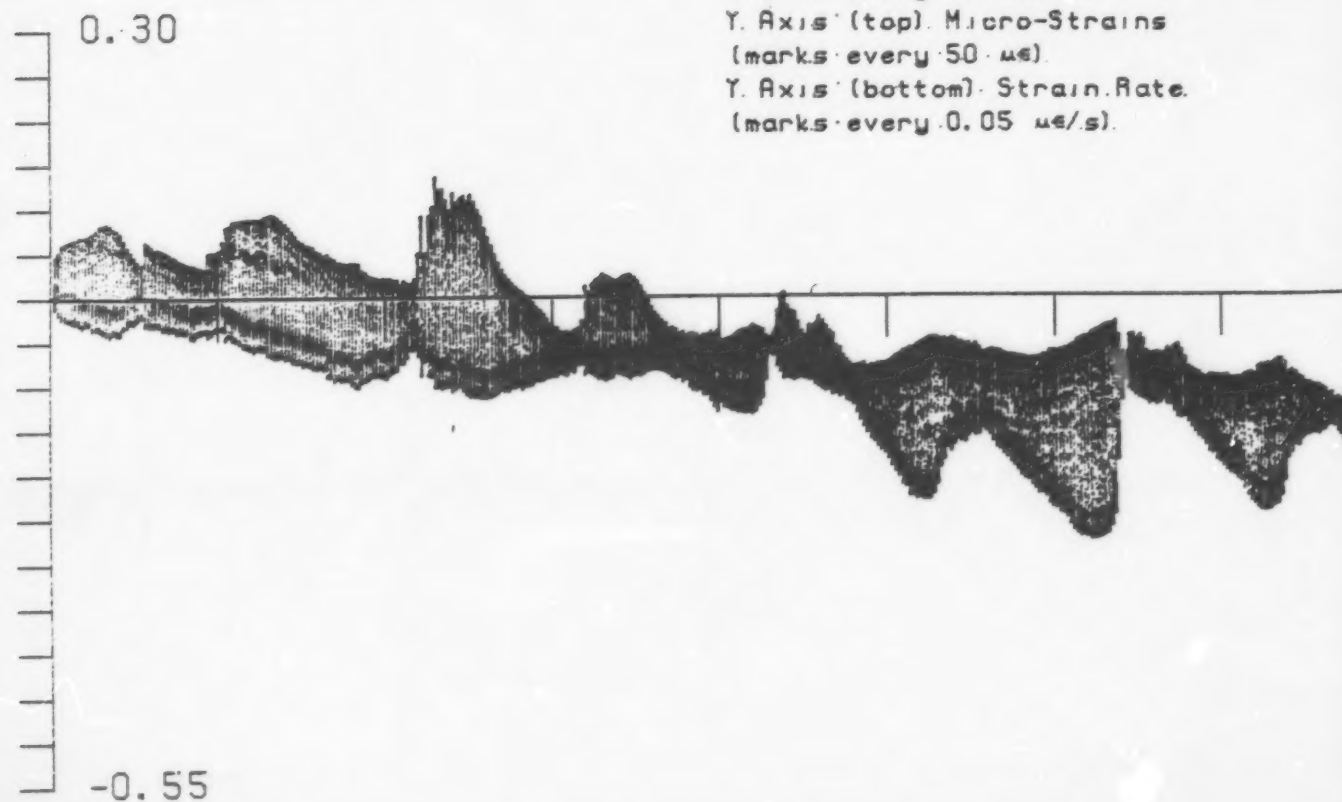
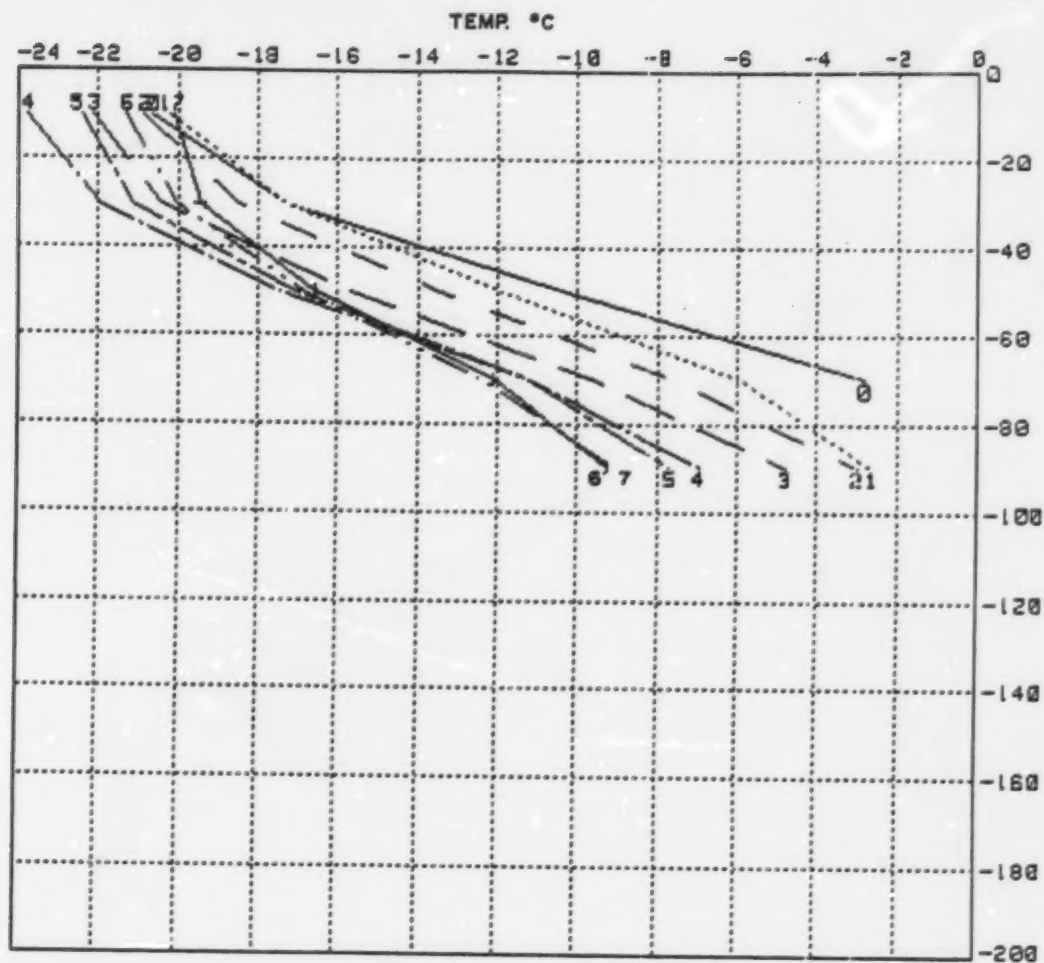


FIGURE 42

NANISIVIC TEMPERATURE PROFILES

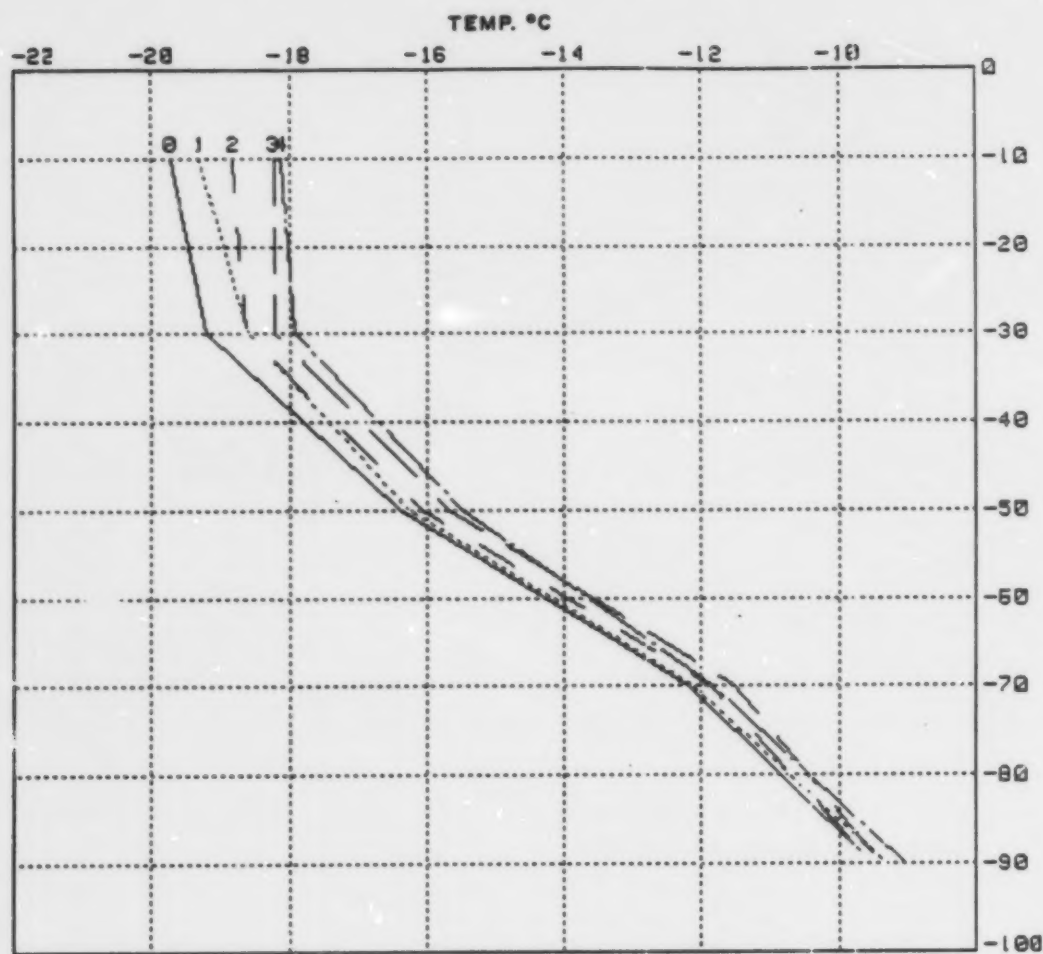


0	Date=5/1	TIME=22:7
1	Date=13/1	TIME=11:52
2	Date=23/1	TIME=12:7
3	Date=27/1	TIME=12:7
4	Date=3/2	TIME=12:7
5	Date=10/2	TIME=12:20
6	Date=24/2	TIME=12:20
7	Date=9/3	TIME=12:5

ICE TEMPERATURE PROFILES (COMPLETE PERIOD)

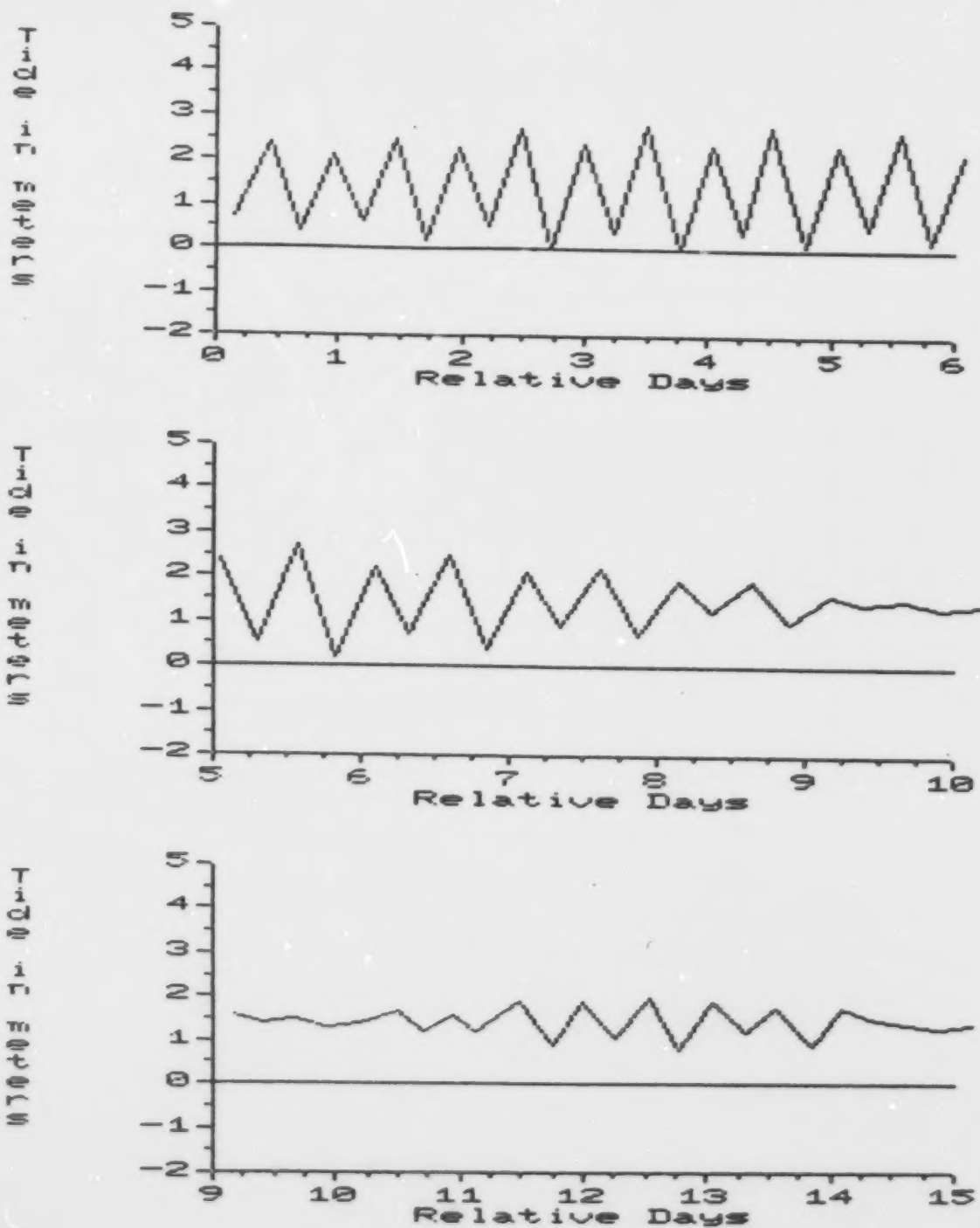
FIGURE 43

NANISIVIC TEMPERATURE PROFILE



0	Date=13/3	TIME=8:20
1	Date=13/3	TIME=20:50
2	Date=14/3	TIME=9:20
3	Date=14/3	TIME=21:50
4	Date=15/3	TIME=10:20

ICE TEMPERATURE PROFILES (MARCH)



TIDES CALCULATED BY CMEL FROM TABLES

FIGURE 46



TYPICAL ICE CONDITIONS - NANISIVIK DOCK

10.0 THE ICE BASIN TESTS

Again the reader is reminded that only the results from those sensors sponsored by Public Works can be published in this report. The results from all the sensors tested will be contained in a separate report which will be available to the public by the end of 1985*. In the description of the work in the ice basin which follows, the other sensors will be referred to, even though results on their actual performance will be excluded.

10.1 SENSOR LAYOUT

The original concept of this project was to test a limited number of different generic sensor types. In the conceptual phase it was imagined that we would compare perhaps only four sensor types [e.g. a thin wide panel, a small hard symmetrical sensor, a strain meter and perhaps a hydraulic disk.] In this context it was not too difficult to imagine one of each sensor type in the high stress area in the ice sheet immediately in front of the reaction face, and arranged in such a way that they would all see very similar stress levels.

As the project matured, it became obvious that each participant had different ideas about which sensors should be tested. As a result we were eventually faced with the problem of accommodating nine sensor types and a total of fifteen sensors as close as possible to the region of high ice stress. The layout eventually chosen and agreed to by the participants is shown in Figure 48, the region shown being about 4 m by 6 m in area. Additional strain meters were also placed further back in the basin as shown in Figure 49.

Several points of rationale were recognized during the planning of the sensor layout, these were:

- . Exxon specifically requested that one of their panels be placed on the reaction structure.

- . Analyses done to examine stress disturbances in ice around sensors were reviewed (Cox and Johnson, 1983; Chen, 1981). These analyses indicated that around hard cylindrical sensors the stress concentration decays to unity at about five to six radii away from the sensor. For the CMEL Hexagonal and the IRAD gauge this distance is about 20 cm. For panels, Chen's analysis indicated a decay of the stress concentration at the panel edge such that the ice stress becomes close to ambient at a distance of about half the panel width.

. Some participants requested that at least one panel be angled to the expected maximum principal compressive stress. Esso/Exxon agreed to orient their second panel in this manner.

. A BP Deltameter and an ARCO array were arranged to be very close to allow comparison of directions of principal stresses.

. An additional BP Deltameter was provided for use close to the structure. This was to provide an early indication of excess creep deformation during long term tests. However it was not a location preferred by BP because of the anticipated high stress gradients, and the possibility of bending of the ice sheet.

. The majority of sensors should be contained within the column of ice that would be formed later in the test programme by cutting slots in the ice on either side of the reaction face.

. Within the constraints of the previously mentioned points, the sensors should be as close to the reaction structure as possible in order to be subject to reasonable stress levels.

Both simple stress analyses and a linearly elastic finite element analysis were performed to examine stress decay away from the structure. Typical results of these analyses are shown as Figures 50 and 51. The results show that up to about 3.6 m [12 ft.] the stress is greater than about 40 to 50% of the nominal ice pressure on the structure and even at 6 m [20 ft.] the ice stress is still about 30% nominal. Referring back to the sensor layout [Figure 48] it will be noted that at least one of each sensor type is within about 2.5 m [8 ft.] of the structure and all sensors are within 5.5 m [18 ft.].

10.2 SENSOR INSTALLATION

The main sensor and strain meter installation took place during the days of February 27th and 28th. The Exxon panel on the structure had been installed the previous week. It should be noted that the original installation did not include either the IRAD gauge or the additional ARCO sensors [4-1, 4-2 and 4-3] or the replacement CMEL Mark IV-C. The general intent was to install the sensors about a week prior to testing so that by using the refrigeration mats the sensors could be well frozen-in.

The methods used to install the sensors were as follows:

- . ARCO 1,2,3, - four six-inch auger holes were drilled through the ice, the already assembled array of discs were lowered into the holes. The ice cuttings from the auger were put into the holes to help speed-up freeze back.

- . CMEL Mark IV-C - Placed in a six-inch auger hole drilled through the ice with ice cuttings placed back in the hole.

- . All panels - chain saw slots through the ice sheet [saline water entered the slots from below].

Note that the salinity of the basin water was about 13 ppt; the salinity of the ice sheet at its mid-point was about 2 ppt.

Later in the test program the IRAD gauge was installed in a 6 cm auger hole [i.e. a close fit]. The additional ARCO discs were installed as follows; ARCO 4-1 and 4-2 in 6 inch deep 6 inch diameter core holes backfilled with fresh water; ARCO 4-3 in the same size holes but backfilled with saline water. These installations were done on March 16, 1984. On March 19, it was apparent that ARCO 4-3 was not properly frozen-in, this was confirmed by examination. The sensor was re-installed in a narrow chain saw slot backfilled with fresh water.

The second CMEL Mark IV-C was installed near the BP 4 location also on March 16, 1984. This installation was into an 10 cm [4 inches] diameter hole 42 cm [16 inches] deep, backfilled with fresh water, both the sensor and hole were cooled down with dry ice.

From the time of installation and during all the tests up to test 20, the refrigeration mats covered the sensors in the primary test area. Refrigeration mats were also used around the loading boom to ensure a well frozen-in condition.

10.3 THE GENERAL TEST STRATEGY

In the original proposal for this project it was envisaged that there would be two separate test periods. One during the coldest time of the winter, say early February with the ice perhaps about 0.5 m thick; and the other later in March when the ice would be warmer and perhaps as much as 0.8 m thick. Each test period was to last about one week, with an average two tests per day. The original plan was to conduct both short term tests and long term [creep tests]. It was also part of the original plan to conduct tests at the end of the programme with the ice

slotted back from the structure in order to approximate a uniaxial stress state on all sensors in front of the structure.

The reality of the Calgary weather during the 1983/84 winter required us to change the test plan. Starting in late January and continuing through February, Calgary had an unusual warm period, when for over thirty days the average daily temperature was above freezing. Because of this warm weather the initial test period was delayed as long as possible in the hope that it would turn seasonally cold again. This it never really did, so about February 20th we decided that sensor installation would start during the week of February 27th and testing one week later. Because of the late start it was expected that only one extended test period would take place. But as it happened we introduced a ten day delay between March 9 and March 19 to allow some replacement and additional sensors to be installed, and to allow what appeared to be a colder trend in weather to take effect.

In total, 22 separate loading tests were performed, of which 3 might be classed as creep tests. The longest test was run for about 4 hours. One reason why creep tests were relatively few was that because of the warm condition of the ice we were afraid to hold the load on for too long in case the ice close to the structure went into tertiary creep.

The last three tests were performed with the slots cut on either side of the structure as planned.

10.4 THE ACTUAL TESTS

A listing of the actual tests performed is shown as Table 10.1. The first three tests were essentially used for de-bugging. The loading, control and data acquisition systems all needed some adjustments. By the time test 4 was commenced all systems were working reasonably well and the Vishay balances were locked; any cumulative effects apparent at the end of the test programme were with respect to this time.

During March 6 a series of gradually increasing loads were applied for relatively short periods. The highest load reached was 76 tons [680 KN]. It was observed during these tests that once steady loads had been reached the total load computed on the basis of hydraulic pressure usually agreed within 5% of the sum of the three shear bar loads [at the supports for the reaction face]. On the other hand, the load carried by the south support was often 50% of the total load [See Table 10.2]. The rest being shared between the other two

supports. It was found that this load imbalance could be corrected to some extent by applying a small lateral load to the ice sheet through the boom at the back end of the basin. This load was applied with a car jack. Table 10.3 summarizes the load imbalance during all tests.

On March 7, 1984 a creep test with the load held at 76 ton [680 KN] for 3 hours was performed. This was followed by a short test up to a higher load of 110 tons [981 KN], which is equivalent to a nominal stress on the structure of 460 kPa [67 psi].

On March 8 it was intended to perform a higher load creep test. The load was raised to 112 tons [996 KN] and the intent was to leave it on for about 2 hours. At about 55 minutes however the boom at the north side of the ice sheet pulled under the sheet and there was a sudden drop in load which led us to abort the test.

The boom was repositioned, and a chain installed across the top of the ice sheet between the two ends of the boom to prevent it from slipping under again [this solution worked well and no further boom problems were encountered]. During a test later that day however it was apparent that there was too much slack in the side cables and it was difficult to apply and hold the load.

For the next test, later that day the slack in the side cables had been taken up and a trial run up to 100 tons was performed to check out the system.

The following day on March 9 another long term test was conducted with a 55 ton load being held for about 60 minutes before a series of cycles of load between 55 and 80 tons. Later that day the plan was to raise the load during a short term test to as close to the 200 ton [1800 KN] capacity as we dared. Test 15 was successfully accomplished with a load of 155 tons [1386 KN] being reached. But the load imbalance was bothering us as only 14% of the load was being carried on the north support and we had some concern about overloading the south support which was carrying 50% of the load, so the load was not pushed higher.

The last test on March 9 was with 80 ton [712 KN] held for 30 minutes.

At this point in the test programme it was decided to stop testing to allow some replacement and additional sensors to be installed. ARCO were particularly concerned about their number 2 installation which appeared to be

reading low, and they requested a pause to allow them to ship-up additional sensors to be installed close by. Also an IRAD gauge had been made available and we wanted to install this and allow it to freeze-in. Furthermore there was promise of some colder weather and a delay of several days might [it was hoped] allow the ice to cool down.

The IRAD gauge and replacement sensors were installed on March 16 and testing recommenced on March 19, 1984. During that day a series of short-term tests with progressively increasing loads were conducted. A total load of 140 tons [1220 KN] was reached by the end of the afternoon. During this test there was a sudden deflection and load reduction on the north support which was indicative of some kind of structural failure. It was obvious that remedial action was going to be required if the final day of testing with the ice slotted was to be accomplished.

The following day the ice was slotted according to plan [Figure 52]. To achieve some structural resistance on the north support a steel cable was attached to it and run the full length of the basin to a large winch truck parked in the Esso car park. A large 30 ton earthmoving machine provided additional ballast to the pulling unit. By this means a load of up to about 20 tons was applied to the north support during the slot tests, this was similar to the reaction load at that support during many of the earlier tests.

Three slot tests were run up to a maximum total load of 151 tons [1346 KN]. This was equivalent to a nominal ice pressure on the reaction structure of about 630 kPa [91 psi]. At this pressure there was no sign of ice failure even though by this time the ice temperature was very close to 0 degrees C. As can be seen from Figure 52 there was however a significant crack which ran through the slotted ice and connected some of the panel sensors [i.e. hexpack and EPR 2]. This crack, as will be discussed later, presented some ambiguity in interpretation of the slotted tests.

10.5 ICE SHEET CONDITIONS AND PROPERTIES

Before presenting and discussing the sensor readings, it is perhaps appropriate to mention typical ice sheet properties and conditions.

During sensor installation, the typical ice sheet thickness beneath the refrigeration mats was fairly uniform at between 0.5 and 0.53 m. In the middle of the basin

however there were some areas of only about 0.45 m; and generally as the north wall of the basin was approached the ice thickness became less [this was the part of the ice sheet most exposed to solar radiation]. But generally speaking, the ice sheet thickness was reasonably uniform at about 0.5 m.

During removal of the sensors about three weeks later the thickness measurements showed a general increase to as much as 0.7 m., with the average of 32 measurements being 0.61 m. The details of this data are given in Appendix C.

Ice temperature data was gathered prior to, and during the tests by means of two thermistor strings frozen into the ice sheet; the lower thermistors on the strings measured water temperature. One string was placed close to the reaction structure under the refrigeration mats; the other was placed in about the middle of the test basin. The details of the temperature data are given in Appendix C. Typical data are as follows; at the beginning of the test period [March 3] the ice away from the refrigeration mats was at -1 degree C; under the mats the ice temperature varied from -4 degrees C at the top to about -2.5 degrees C at the bottom; at the end of testing [March 20] the ice in the middle of the basin was at about -0.5 degrees C; near the sensors the ice temperature was about -1.5 degrees C. Note that the refrigeration mats had been removed on the morning of March 20 in order to slot the ice.

Ice salinity data is also given in Appendix C. Typically ice salinity was about 0.6 ppt near the surfact [or even lower] and about 2 ppt for most of the ice sheet thickness. The water salinity was about 13 ppt.

For most of the tests the ice was free from any significant cracks. Some surface cracking occurred near the corners of the structure during the rapid load reduction when the boom slipped under the ice during test 11. These cracks were cored however and it appear as though they were limited to the surfact layer [about a 2-3 inch thickness of fairly fresh ice]. A much deeper crack system developed during test 19 when the structure deformed significantly. One of these cracks ran through the sensor area and is shown on Figure 52. It is assumed that this crack was through the full ice sheet thickness.

10.6 DATA REDUCTION METHODOLOGY AND PRIMARY RESULTS FORMAT

The main data acquisition system enabled voltage outputs from the various sensors to be recorded on the H.P. micro-diskettes [usually at a scanning rate of 1 Hz]. After each test

these recorded voltages could be played back through the computer and a voltage plot printed for each sensor. This was always done in order to see if each sensor was responding properly before proceeding to the next test. These voltages were subsequently combined with the calibration factors supplied for each sensor to create plots of sensor readings in engineering units. The calibration factors used for each sensor are shown in Table 10.4.

The abbreviated sensor labels are explained in Table 10.5. The calibration factors are based on the information given by the suppliers and incorporate inclusion factors [if any] required to convert from stress on the sensor to a stress in the ambient ice. In some cases, where a panel protruded beyond the ice sheet thickness then an additional correction factor is also incorporated.

A typical plot of shear bar [load cell] readings for test number 6 is presented as Figure 53. The interval statistics plotted below the figure relate to the time intervals defined by the vertical dashed lines on the plots. These intervals were selected during the data analysis primarily using the criterion of load plateaux. Comparisons between sensor readings and loads applied to the ice were always made for the same time intervals using the mean values calculated for each interval.

For each test, several intervals for comparison were defined. A master table giving sensor readings in engineering units for each time interval of comparison was compiled and is presented as Table 10.6. The sensor labels are those defined in Table 10.5.

The aforementioned components of data [the sensor computer plots, and Table 10.6 which indicates mean sensor readings at each time interval], can be considered to be the "primary" results of how typically each sensor responded, all the sensor plots from two typical tests are included in the main body of this report as Figures 54 to 57. These are the "primary results for test 9 [the creep test] and test 15 [a typical high load test]. To save space, the interval statistics have been removed from these plots, but a complete set of plots for all tests together with the interval statistics is given in reference 21

We will now present an approach used to assess how well each sensor appeared to measure the ice pressure acting on it.

10.7 ANALYSIS OF RESULTS

Unslotted Tests

As already discussed, in order to know if a sensor reading is plausible, then the stress field in the ice sheet needs to be known. One might expect at first sight that an analysis for edge loading of a large plate [or semi-infinite plate] would suffice. Furthermore, for the short term tests at least, that an elastic solution would be a reasonably good approximation. This approach was used prior to the tests to get an appreciation of how quickly the theoretical stress in the ice compared to the nominal ice pressure on the reaction face [this is known from the measured loads]. Had the experiments been perfectly performed this symmetrical, elastic finite element analysis would have been used as a first step in examining the results.

Unfortunately, as already mentioned for most tests the loads on the three frames supporting the reaction face were not equal [see Table 10.2 and 10.3]. For most tests the south reaction frame carried about 50% of the total load compared to the 33% it ideally should have carried. The result of this unsymmetrical load reaction was presumably an unsymmetrical stress distribution in the ice sheet.

In order to examine the extent of this lack of symmetry and its effect on stress levels at sensor locations, further finite element analyses were performed. In these analyses the actual load cell values for a given test and interval were used, and the stiffness of the reaction face as a two-dimensional beam was included. Analyses were performed for tests 9, 15 and 19; contours of predicted ice stress were plotted for each of the principal stresses, and also for σ_y [the stress at right angles to the reaction face, i.e. in the direction of loading] and σ_x . Typical results are presented as Figures 58 to 62. Also shown on the contour plots [near the load face] are the actual sensor locations. So if we believe the calculated stress distributions we now have a method of comparing actual sensor readings with stress in the ice based on the actual loads on the reaction structure. Perhaps the main criticism with this approach is the assumption that ice behaves as a linearly elastic material. How would the stress distribution change if at some stress level the ice behaved plastically [this approach has often been used to represent the ductile deformation of ice]? We have not run a finite element analysis using this approach, however the analytical solution by Ralston [1973] for a circular indenter and a semi-infinite sheet might be used as a guide. Figure 50 shows the results from Ralston's analysis comparing stress decay along the centre line for both elastic and plastic solutions. A simple interpretation of these two

curves suggests that the stress at a certain point out in the ice could be higher than that predicted by the elastic solution, but any pseudo-plasticity effects should not lead to a lower stress than that predicted by the elastic solution. If then, in the examination of the results from each sensor a definite trend indicating an over prediction [compared to the elastic solution] was seen, then this would be a good indication that a plasticity approach should have been used. In reviewing the results which will follow, this has not been found to be the case and therefore this suggests that the elastic solution could be a reasonable basis for comparison.

In order to make as concise a comparison as possible of sensor readings with ice stress, some further steps of analysis were taken. In examining the stress distributions from the finite element analyses, the ratios for the stress predicted at a particular sensor to the nominal ice pressure on the reaction face were tabulated. Values of these ratios are presented in Table 10.7. It will be noted that for most sensors, the variation in this ratio between tests is quite small. It is suggested that within the limits of accuracy of this experiment that the average value of this ratio [for each sensor] could be used to convert from stress recorded by the sensor to nominal ice pressure on the load face. In the tests examined the error in using the average value would be typically less than 10%.

It was also recognized that for most tests, [i.e. after test 6] the load imbalance between reaction frames was similar to the imbalances for the finite element analyses performed. Therefore to interpret the rest of tests 7 to 19 the average ratio for each sensor shown in Table 10.7 was used to predict nominal ice pressure on the reaction face from the sensor reading. For tests 4 to 6 inclusive, the load distribution between north and south was more even and therefore the stress ratio predicted by the symmetrical finite element analysis was used.

The specific methodology used is as follows, and is essentially summarized in Table 10.8 which is an example of the values calculated for the Weir-Jones Ideal stress panel [WJ-1].

For a specific test and interval number the stress ratio or factor discussed above is selected. This is based either on the symmetrical finite element analysis, or an actual finite element analysis for that test, or on the average value from all the unsymmetrical analyses.

The next step is to tabulate the actual sensor reading in kPa which comes from the data plots and/or the interval statistics summarized in Table 10.6. The next step is to predict the ice pressure on the structure from the sensor reading by dividing by the stress factor or ratio. For the WJ1 sensor this means dividing by either 0.63 or about 0.5. If it wasn't for a small correction for ice thickness this would be the value to compare with actual nominal ice pressure on the structure. It will be seen from Table 10.8 that for test 4 interval 1 the nominal ice pressure measured on the structure is 23.9 kPa whereas the uncorrected pressure predicted from the sensor reading is 30.6 kPa. Now for all tests, the calculated nominal ice pressure on the structure is based on the actual load divided by structure width and a nominal ice thickness of 0.7 m. If then the thickness of the sensor location is different from 0.7 a correction needs to be made. In this case the actual thickness at the sensor location was less than 0.7 and is taken as 0.6 m for all tests, so the corrected predicted ice pressure on the structure is obtained by multiplying by 0.6 divided by 0.7.

Using this approach Table 10.8 is completed for the representative sampling of test intervals used. Percentage differences between predicted and actual can be calculated and an average difference [whether plus or minus] calculated. In this case the average percentage difference is about 13%. A more striking way of presenting this analysis is graphically, as shown in Figure 63. The line at 45 degrees represents perfect agreement between pressure on the structure predicted by the sensor and actual pressure on the structure calculated from the load cells.

Similar graphs of sensor performance are presented for the other two panels as Figures 64 and 65, for tests 4 to 19 inclusive. The tables, on which the figures are based, are contained in reference 21.

Slotted Tests

It will be recalled that tests 20, 21 and 22 were conducted with the ice slotted. This was done to simplify the analysis of the stress distribution and create a more uniform stress field for sensor comparison. This objective was not completely successful for the following reasons:

- . A crack was present in the slotted ice (See Figure 52).
- . The load reactions across the reaction face were not equal.
- . To perform this test the refrigeration mats had to be removed. Some sensors which were exposed to high ambient temperatures and solar radiation started to exhibit loss of contact with the ice near the surfact due to ice melting.

Various attempts were made to rationalize the interpretation of the slotted test including calculation of an unsymmetrical stress distribution assuming the crack was completely through the ice sheet. The most consistent results were obtained for those sensors close to the reaction face if it was assumed that the crack changed the stress distribution. For those sensors furthest from the reaction face the best comparisons assumed the stress was uniform and equal to the nominal ice pressure on the structure.

Plots of sensor performance for the slotted tests are presented as Figures 66 to 68; again the tabulated values on which these plots are based are presented in reference 21.

10.8 DISCUSSION OF RESULTS

This section is organized in such a way that the results obtained from the ice pressure sensors are discussed on a sensor-by-sensor basis. Problems of interpretation and other issues relating to sensor performance are introduced and discussed where relevant. The order of discussion is somewhat random, except that the results which are fairly straightforward are presented first.

10.8.1 The Weir-Jones Ideal Panel

This is a 0.5 m by 1.0 m panel which averages the stress through the entire ice sheet. The panel was positioned 1.6 m from the reaction face. Figure 63 summarizes the performance of the panel during the main tests. The average percent difference from perfect agreement is about 13%. During the longest test [9], the apparent error at maximum load was only about 2%; during the highest load test, the difference was 6%.

Comparison of the WJ1 stress responses with the patterns of load versus time indicates good similarity and no apparent lag in response.

The results obtained during the slotted test are not easily interpreted. The WJ1 panel, was situated to the north of the crack [See figure 52]. If we allow for the presence of the crack and assume that the north reaction load is stressing the ice on the north side of the crack, then the comparison shown in Table 10.9 is obtained. This suggests the sensor is reading too high. On the other hand if we assume the crack has no influence on the stress distribution, and further, that the stress in the slotted ice is simply the nominal ice pressure on the structure then the comparison shown in Table 10.10 is obtained. Using these assumptions the sensor seems to be reading too low.

All the sensors on the north side are reading too low when compared with nominal ice stress, but the response of the WJ1 sensor is quite linear. Considering its performance in the unslotted ice, it is probably reading close to the actual ice stress [which probably lies somewhere between the two extreme assumptions described above]. Because of the ambiguity in the stress in the ice no percentage error or difference values are quoted for those sensors on the north side of the crack [for the slotted tests].

In general, the WJ1 sensor displayed a good linear response, the stress values it measured seemed plausible, and its output remained steady during the creep test. The cumulative zero error during test programme was about 20 kPa, i.e. about 5% of the maximum stress applied during the tests.

10.8.2 The Arctec Hexpack

This is a thin wide panel 1 m by 2 m. As shown in Figure 5 it was installed on the centre line of the ice sheet 2.36 m from the reaction face. Two signals were received from the Hexpack, one giving the average ice stress for a band 25 cm wide across the sensor, the centre of which was 12.5 cm below the ice surface; the other signal was for a similar band with its centre 37.5 cm below the ice surface.

In interpreting the readings from the Hexpack, the simple arithmetic mean of the two sets of ice pressures [AHX1 and AHX2] was used to compare with the predicted ice pressure calculated from the structure loads.

The performance of the Hexpack during the main series of tests is summarized in Figure 64. The average apparent error was 11% with no bias to reading either low or high.

The performance of the Hexpack during the slot test is summarized in Figure 67. Only the stresses on the lower part of the sensor are plotted because the upper part had lost contact with the ice due to melting. Furthermore, even this response is low, but there are several reasons why the results are unreliable. First, the solar radiation acting on the upper part of the sensor above the ice may have warmed-up the sensor sufficiently that the slot in which it rested became unable to transmit ice stress across the sensor. Second, the crack in the ice went through the sensor location and may have resulted in the same effect.

In general, during the main test series the Hexpack responded in an apparent linear fashion to the loads. The

stresses measured appeared reasonable. The average sensor output during the creep test was reasonably steady [Figure 54]. The cumulative zero error during the test programme was about 4.5 kPa

10.8.3 The Medof Panel

The Medof panel was made especially for this project, and was 0.5 m wide by 1.0 m long. It was located as shown in Figure 5, 1.6 m from the reaction face, about 1.0 m south of the centre line. This panel averages the ice pressure through the ice sheet thickness and a correction factor is required if the ice thickness is less than the panel length [as in this case].

In general, as can be seen from the plots of panel response, this panel faithfully reproduced the shape of the plots of applied load. During the creep test however there was a distinct increase in panel response during the period [2.5 hours] of constant load. At the beginning of the period the panel reading was 120 kPa, at the end it was 159 kPa. Furthermore, as can be seen from Figure 65, the panel appeared to read low; the average percentage difference from predicted ice pressure being about -48%.

This low response also shows up in the results of the slot tests which are shown in Figure 68. Although the sensor appears to read low, its response is reasonably linear, and it is difficult to explain the sensor performance [Before finalizing this report is it intended to double check the calibration factors for this panel].

Cumulative zero error for the Medof panel during the tests was 19.8 kPa.

TABLE 10.1
TEST MATRIX LOG

TEST	RUN	DATE	TIME	TOTAL SCAN TIME	TEST LOADING		COMMENTS
					LOAD	DUR.	
1	1	Mar 4	1515	30 m.	12 tons *	5 m.	Test shut down half-way through due to different ram loads. Test was then cont'd.
1	2	Mar 4	1545	15 m.	12 tons ramp to 0	10 m. 5 m.	
1	3	Mar 4	1705	40 m.	ramp up 18 tons ramp dn	5 m. 30 m. 5 m.	No test # 2 performed
3	1	Mar 5	1100	35 m.	ramp up 12 tons ramp 18 tons ramp 24 tons ramp dn	5 m. 5 m. 5 m. 5 m. 5 m. 5 m.	
4	1	Mar 6	0900	20 m.	ramp up 18 tons ramp dn	5 m. 10 m. 5 m.	Vishay balances locked. Cumulative offsets with respect to this point.
5	1	Mar 6	1100	40 m.	ramp up 18 tons 32 tons ramp dn	5 m. 5 m. 25 m. 5 m.	
6	1	Mar 6	1300	40 m.	ramp up 32 tons 40 tons 50 tons 60 tons ramp dn	5 m. 4 m. 4 m. 4 m. 4 m. 5 m.	
7	1	Mar 6		15 m.	ramp up 5 tons 23 tons	3 m. 1 m. 3 m.	Mislabelled on disc as test 7 run 1. Date also mislabelled as Mar 6 for system A.
8	2	Mar 7	0900	10 m.	ramp up 32 tons	5 m. 5 m.	

* Note: These loads are approximate

TABLE 10.1(CONTD.)

TEST	RUN	DATE	TIME	TOTAL SCAN TIME	TEST LOADING	DUR.	COMMENTS
					LOAD		
9	1	Mar 7	1100	4.5 hr	ramp up 60 tons ramp dn 30 tons ramp dn zero	10 m 3 hr 10 m 10 m 10 m 1 hr	Creep Test
10	1	Mar 7	1600		ramp up 60 tons ramp up 85 tons ramp dn	15 m 2 m 5 m 5 m	
11	1	Mar 8	0830	2.5 hr	ramp up 85 tons ramp dn 50 tons ramp dn zero	10 m 45 m 5 m 10 m 5 m 1 hr	Boom failure at 1010. Shear failure on ice bottom next to boom. Boom pulling under.
12	1	Mar 8	1445				Hydraulic system could not get load up.
13	1	Mar 8	1540	1 hr	ramp up 100 tons ramp dn zero	20 m 5 m 5 m 30 m	Short 100 ton load
14	1	Mar 9	1145	180 m	ramp up 50 tons ramp up 75 tons ramp dn 50 tons ramp up 75 tons ramp dn 50 tons ramp up 75 tons ramp dn zero	10 m 60 m 5 m 2 m 2 m 2 m 5 m 2 m 2 m 2 m 2 m 4 m 30 m	

TABLE 10.1(CONTD.)

TEST	RUN	DATE	TIME	TOTAL SCAN TIME	TEST LOADING		COMMENTS
					LOAD	DUR.	
15	1	Mar 9	1500	40 m	ramp up 132 tons ramp dn decay	20 m 1 m 5 m	
16	1	Mar 9		60 m	ramp up 80 tons ramp dn	15 m 30 m 5 m	Had some trouble with the side load jacks. Ramped to 50 tons while re- positioning jacks, then up to 80 tons.
17	1	Mar 19	1035	30 m	ramp up 30 tons 50 tons ramp dn	10 m 5 m 5 m 10 m	System checkout
18	1	Mar 19	1420	30 m	ramp up 100 tons ramp dn	15 m 5 m 10 m	
19	1	Mar 19	1610	30 m	ramp up 150 tons ramp dn	15 m	Structure failure. North support listed.
20	1	Mar 20	1300	25 m	ramp up 10 tons		Slot test
21	1	Mar 20	1400	45 m	ramp up 70 tons ramp dri		Slot test Cable failed 30 min. into the test.
22	1	Mar 20	1525	90 m	ramp up		Shear bar offsets at start of test: SB1 3.1 tons SB2 0.5 tons SB3 0.0 tons

TABLE 10.2
LOAD SUMMARY

TEST #	INT. #	LOAD (KN) USING RAM PRESSURE	SUPPORT LOADS (KN)			TOTAL SUPPORT LOAD (KN)
			NORTH	CENTRE	SOUTH	
4.1	1	71.1	34.1	4.3	12.6	51.0
	2	190.5	66.6	12.3	78.1	157.0
5.1	1	183.0	67.6	8.4	82.3	158.3
	2	321.4	118.1	20.5	162.0	300.6
6.1	1	443.8	167.3	47.4	204.4	419.1
	2	524.6	178.0	71.4	256.1	505.5
	3	680.5	211.1	135.2	334.7	681.0
7.1	1	38.0	-1.6	2.5	41.6	42.5
	2	326.5	107.5	21.3	167.0	295.8
8.1	1	176.9	19.2	24.2	102.0	145.4
	2	290.0	42.8	39.1	142.4	224.3
9.1	1	670.2	196.7	144.9	336.4	678.0
	2	352.8	106.0	43.7	192.4	342.1
	3	1.4	13.1	2.9	5.3	21.3
	4	2.2	7.4	2.6	12.8	22.8
10.1	1	585	201.0	127.3	295.3	623.6
	2	829	279.3	224.0	374.9	878.2
	3	936	302.9	263.2	414.9	981.0
11.1	1	953.6	296.0	283.3	416.3	995.6
	2	-	-	-	-	-
12.1	1	379	73.5	13.8	168.9	256.2
	2	553	81.5	30.2	361.7	473.4
	3	576	88.2	39.1	412.1	539.4
13.1	1	326.2	89.6	53.1	171.95	314.7
	2	367.5	112.3	68.8	168.1	349.2
	3	1129.4	249.2	351.7	597.7	1198.6
14.1	1	549.6	88.9	146.5	260.1	495.5
	2	714.6	118.9	213.9	379.3	712.1

TABLE 10.2 (CONTD.)
(continued)

LOAD SUMMARY

TEST #	INT. #	LOAD (KN) USING RAM PRESSURE	SUPPORT LOADS (KN)			TOTAL SUPPORT LOAD (KN)
			NORTH	CENTRE	SOUTH	
15.1	1	587.9	94.5	158.7	330.1	583.3
	2	1150.8	233.9	372.9	551.5	1158.3
	3	1381.5	202.7	473.2	710.3	1386.2
16.1	1	666.0	90.1	202.4	337.4	629.9
	2	916.3	179.7	305.9	372.7	858.3
17.1	1	327.1	58.2	49.2	150.2	257.6
	2	535.8	70.1	119.8	280.3	470.2
	3	535.8	56.6	121.4	284.3	462.3
18.1	1	649.1	86.3	160.8	276.5	523.6
	2	824.9	64.9	250.3	407.7	722.9
	3	1128.5	152.7	391.4	500.6	1044.7
19.1	1	517.1	59.3	160.9	209.3	429.5
	2	1102.3	174.9	408.7	434.1	1017.7
	3	1319.1	59.0	484.2	675.0	1218.2
20.1	1	203.5	53.1	22.9	75.9	151.9
	2	308.4	83.3	49.7	134.4	267.4
	3	436.9	115.6	91.4	215.3	422.3
21.1	1	265.2	81.1	44.1	118.7	243.9
	2	408.2	101.6	90.4	217.0	409.0
	3	524.3	120.3	134.2	287.7	542.2
	4	663.3	172.8	184.4	356.5	713.7
22.1	1	200.8	83.2	16.0	46.9	146.1
	2	325.9	81.1	52.4	119.7	253.2
	3	435.1	75.5	91.8	218.4	385.7
	4	548.7	88.8	133.5	306.2	528.5
	5	667.2	88.4	177.8	391.0	657.2
	6	781.8	89.8	224.5	474.4	788.8
	7	889.4	93.2	269.5	548.4	911.1
	8	1022.0	109.8	327.5	542.4	979.7
	9	1138.2	140.5	382.4	681.3	1204.2
	10	1265.9	166.8	437.4	741.6	1345.8

TABLE 10.3
LOAD IMBALANCE SUMMARY

TEST #	INT. #	TOTAL LOAD (KN)	LOAD SHARING NORTH	LOAD SHARING CENTRE	LOAD SHARING SOUTH	TEST #	INT. #	TOTAL LOAD (KN)	LOAD SHARING NORTH	LOAD SHARING CENTRE	LOAD SHARING SOUTH
4.1	1	51.0	66.8	8.4	24.7	18.1	1	523.6	16.5	30.7	52.8
	2	157.0	42.4	7.8	49.7		2	722.9	9.0	34.6	56.4
5.1	1	158.3	42.7	5.3	52.0		3	1044.7	14.6	37.5	48.0
	2	300.6	39.3	6.8	53.9	19.1	1	429.5	13.8	37.5	48.7
6.1	1	419.1	40.0	11.3	48.8		2	1017.7	17.2	40.2	42.5
	2	505.5	35.2	14.1	50.7		3	1218.2	4.8	39.7	55.4
7.1	1	42.5	0	5.9	97.9	20.1	1	151.9	35.0	15.1	50.1
	2	295.8	36.3	7.2	56.5		2	267.4	31.2	18.6	50.3
8.1	1	145.4	13.2	16.7	70.1		3	422.3	27.4	21.6	51.0
	2	224.3	19.0	17.4	63.5	21.1	1	243.9	33.3	18.1	48.5
9.1	1	678.0	29.0	21.4	49.6		2	409.0	24.8	22.1	53.1
	2	342.1	31.0	12.8	56.2		3	542.2	22.2	24.6	53.1
	3	21.3	62.0	13.6	24.9		4	713.7	24.2	25.8	50.0
	4	22.8	32.5	11.4	56.1	22.1	1	146.1	57.0	11.0	32.1
10.1	1	623.6	32.2	20.4	47.4		2	253.2	32.0	20.7	47.2
	2	878.2	31.8	25.5	42.7		3	385.7	19.6	23.8	56.6
	3	981.0	30.9	26.8	42.3		4	528.5	16.8	25.3	58.0
11.1	1	995.6	29.7	28.5	41.8		5	657.2	13.5	27.1	59.5
	2	-	28.7	5.4	66.0		6	788.8	11.4	28.5	60.1
12.1	1	256.2	17.2	6.4	76.4		7	911.1	10.2	29.6	60.2
	2	473.4	16.4	7.2	76.4		8	979.7	11.2	33.4	55.4
13.1	1	314.7	28.5	16.9	50.3		9	1204.2	11.7	31.8	56.6
	2	349.2	32.2	19.7	48.1		10	1345.8	12.4	32.6	55.1
	3	1198.6	20.8	29.3	47.4						
14.1	1	495.5	17.9	29.6	52.4						
	2	712.1	16.7	30.0	53.2						
15.1	1	583.3	16.2	27.2	56.6						
	2	1158.3	20.1	32.1	47.6						
	3	1386.2	14.6	34.1	51.2						
16.1	1	629.9	14.3	32.1	53.6						
	2	858.3	20.9	35.6	43.4						
17.1	1	257.6	22.6	19.1	58.3						
	2	470.2	14.9	25.5	59.6						
	3	462.3	12.2	26.3	61.5						

* Negative load recorded on north support

TABLE 10.4

SYSTEM CALIBRATION FACTORS

SENSOR LABEL													
NO.	CM2.3	CM2.1	CM2.2	NOF1	NOF2	NOF3	WJ1	AB11	AB12	AB13			
1.1	649 KPA/V	NOT INSTAL.	NOT INSTAL.	165.3 KPA/V	191.4 KPA/V	223 KPA/V	52.5 KPA/V	108 KPA/V	106 KPA/V	104 KPA/V			
1.2	649 KPA/V	NOT INSTAL.	NOT INSTAL.	165.3 KPA/V	191.4 KPA/V	223 KPA/V	52.5 KPA/V	108 KPA/V	106 KPA/V	104 KPA/V			
1.3	649 KPA/V	NOT INSTAL.	NOT INSTAL.	165.3 KPA/V	191.4 KPA/V	223 KPA/V	52.5 KPA/V	108 KPA/V	106 KPA/V	104 KPA/V			
3.1	649 KPA/V	NOT INSTAL.	NOT INSTAL.	165.3 KPA/V	191.4 KPA/V	223 KPA/V	52.5 KPA/V	108 KPA/V	106 KPA/V	104 KPA/V			
4.1	649 KPA/V	NOT INSTAL.	NOT INSTAL.	165.3 KPA/V	191.4 KPA/V	223 KPA/V	52.5 KPA/V	108 KPA/V	106 KPA/V	104 KPA/V			
5.1	649 KPA/V	NOT INSTAL.	NOT INSTAL.	165.3 KPA/V	191.4 KPA/V	223 KPA/V	52.5 KPA/V	108 KPA/V	106 KPA/V	104 KPA/V			
6.1	649 KPA/V	NOT INSTAL.	NOT INSTAL.	165.3 KPA/V	191.4 KPA/V	223 KPA/V	105 KPA/V	108 KPA/V	106 KPA/V	207 KPA/V			
7.1	649 KPA/V	NOT INSTAL.	NOT INSTAL.	165.3 KPA/V	191.4 KPA/V	223 KPA/V	105 KPA/V	108 KPA/V	106 KPA/V	207 KPA/V			
8.1	649 KPA/V	NOT INSTAL.	NOT INSTAL.	165.3 KPA/V	191.4 KPA/V	223 KPA/V	105 KPA/V	108 KPA/V	106 KPA/V	207 KPA/V			
9.1	649 KPA/V	NOT INSTAL.	NOT INSTAL.	165.3 KPA/V	191.4 KPA/V	223 KPA/V	105 KPA/V	108 KPA/V	106 KPA/V	207 KPA/V			
10.1	649 KPA/V	NOT INSTAL.	NOT INSTAL.	165.3 KPA/V	191.4 KPA/V	223 KPA/V	105 KPA/V	108 KPA/V	106 KPA/V	207 KPA/V			
11.1	649 KPA/V	NOT INSTAL.	NOT INSTAL.	165.3 KPA/V	191.4 KPA/V	223 KPA/V	105 KPA/V	108 KPA/V	106 KPA/V	207 KPA/V			
12.1	649 KPA/V	NOT INSTAL.	NOT INSTAL.	165.3 KPA/V	191.4 KPA/V	223 KPA/V	105 KPA/V	108 KPA/V	106 KPA/V	207 KPA/V			
13.1	649 KPA/V	NOT INSTAL.	NOT INSTAL.	165.3 KPA/V	191.4 KPA/V	223 KPA/V	105 KPA/V	108 KPA/V	106 KPA/V	207 KPA/V			
14.1	649 KPA/V	NOT INSTAL.	NOT INSTAL.	165.3 KPA/V	191.4 KPA/V	223 KPA/V	105 KPA/V	108 KPA/V	106 KPA/V	207 KPA/V			
15.1	649 KPA/V	NOT INSTAL.	NOT INSTAL.	165.3 KPA/V	191.4 KPA/V	223 KPA/V	105 KPA/V	108 KPA/V	106 KPA/V	207 KPA/V			
16.1	649 KPA/V	NOT INSTAL.	NOT INSTAL.	165.3 KPA/V	191.4 KPA/V	223 KPA/V	105 KPA/V	108 KPA/V	106 KPA/V	207 KPA/V			
17.1	649 KPA/V	1563 KPA/V	807 KPA/V	165.3 KPA/V	191.4 KPA/V	223 KPA/V	105 KPA/V	108 KPA/V	106 KPA/V	207 KPA/V			
18.1	649 KPA/V	1563 KPA/V	807 KPA/V	165.3 KPA/V	191.4 KPA/V	223 KPA/V	105 KPA/V	108 KPA/V	106 KPA/V	207 KPA/V			
19.1	649 KPA/V	1563 KPA/V	807 KPA/V	165.3 KPA/V	191.4 KPA/V	223 KPA/V	211 KPA/V	108 KPA/V	106 KPA/V	207 KPA/V			
20.1	649 KPA/V	1563 KPA/V	807 KPA/V	165.3 KPA/V	191.4 KPA/V	223 KPA/V	211 KPA/V	108 KPA/V	106 KPA/V	207 KPA/V			
21.1	649 KPA/V	1563 KPA/V	807 KPA/V	165.3 KPA/V	191.4 KPA/V	223 KPA/V	211 KPA/V	108 KPA/V	106 KPA/V	207 KPA/V			
22.1	649 KPA/V	1563 KPA/V	807 KPA/V	165.3 KPA/V	191.4 KPA/V	223 KPA/V	211 KPA/V	108 KPA/V	106 KPA/V	207 KPA/V			

Note: Sensor sensitivities reduced due to incomplete ice contact as follows:

Sensor	Sensor Length	Ice Thickness	Sensitivity Reduction Factor	$\left(\frac{\text{Thickness in Ice}}{\text{Sensor Length}}\right)$
NOF 1	1m	0.60m	0.60	
WJ 1	1m	0.59m	0.59	

TABLE 10.4 (CONT.)

SEVEN COORDINATION FACTORS

SENSOR LABEL												
TEST NO.	W.P.	S01	S02	S03	K1	K2	EPR1	EPR2	CH01	CH02		
1.1	-2.76 MPa/V	637.8 kN/V	-72.5 kN/V	-74.5 kN/V	-0.267 kN/V	-0.109 kN/V	180 kN/V	163 kN/V	1250 kN/V	962 kN/V		
1.2	-2.76 MPa/V	637.8 kN/V	-72.5 kN/V	-74.5 kN/V	-0.267 kN/V	-0.109 kN/V	180 kN/V	163 kN/V	1250 kN/V	962 kN/V		
1.3	-2.76 MPa/V	637.8 kN/V	-72.5 kN/V	-74.5 kN/V	-0.267 kN/V	-0.109 kN/V	180 kN/V	163 kN/V	1250 kN/V	962 kN/V		
3.1	-2.76 MPa/V	637.8 kN/V	-72.5 kN/V	-74.5 kN/V	-0.267 kN/V	-0.109 kN/V	180 kN/V	163 kN/V	1250 kN/V	962 kN/V		
4.1	-2.76 MPa/V	637.8 kN/V	-72.5 kN/V	-74.5 kN/V	-0.267 kN/V	-0.109 kN/V	180 kN/V	163 kN/V	1250 kN/V	962 kN/V		
5.1	-2.76 MPa/V	637.8 kN/V	-72.5 kN/V	-74.5 kN/V	-0.267 kN/V	-0.109 kN/V	180 kN/V	163 kN/V	1250 kN/V	962 kN/V		
6.1	-6.88 MPa/V	637.8 kN/V	-72.5 kN/V	-185.2 kN/V	-0.267 kN/V	-0.109 kN/V	180 kN/V	163 kN/V	1250 kN/V	962 kN/V		
7.1	-6.88 MPa/V	637.8 kN/V	-72.5 kN/V	-185.2 kN/V	-0.267 kN/V	-0.109 kN/V	180 kN/V	163 kN/V	1250 kN/V	962 kN/V		
8.1	-6.88 MPa/V	637.8 kN/V	-72.5 kN/V	-185.2 kN/V	-0.267 kN/V	-0.109 kN/V	180 kN/V	163 kN/V	1250 kN/V	962 kN/V		
9.1	-6.88 MPa/V	637.8 kN/V	-72.5 kN/V	-185.2 kN/V	-0.267 kN/V	-0.109 kN/V	180 kN/V	163 kN/V	1250 kN/V	962 kN/V		
10.1	-13.77 MPa/V	637.8 kN/V	-72.5 kN/V	-185.2 kN/V	-0.267 kN/V	REMOVED	REMOVED	163 kN/V	1250 kN/V	REMOVED		
11.1	-13.77 MPa/V	637.8 kN/V	-72.5 kN/V	-185.2 kN/V	-0.267 kN/V	REMOVED	REMOVED	4491 kN/V	5000 kN/V	3850 kN/V		
12.1	-13.77 MPa/V	637.8 kN/V	-72.5 kN/V	-185.2 kN/V	-0.267 kN/V	REMOVED	REMOVED	1123 kN/V	5000 kN/V	3850 kN/V		
13.1	-13.77 MPa/V	637.8 kN/V	-72.5 kN/V	-185.2 kN/V	-0.267 kN/V	REMOVED	REMOVED	1123 kN/V	1250 kN/V	3850 kN/V		
14.1	-13.77 MPa/V	637.8 kN/V	-181.2 kN/V	-185.2 kN/V	-0.267 kN/V	REMOVED	REMOVED	1123 kN/V	1014 kN/V	962 kN/V		
15.1	-13.77 MPa/V	637.8 kN/V	-181.2 kN/V	-185.2 kN/V	-0.267 kN/V	REMOVED	REMOVED	1123 kN/V	1250 kN/V	962 kN/V		
16.1	-13.77 MPa/V	637.8 kN/V	-181.2 kN/V	-185.2 kN/V	-0.267 kN/V	REMOVED	REMOVED	1123 kN/V	1014 kN/V	962 kN/V		
17.1	-13.77 MPa/V	637.8 kN/V	-283.1 kN/V	-289.4 kN/V	-0.267 kN/V	REMOVED	REMOVED	160 kN/V	1014 kN/V	962 kN/V		
18.1	-13.77 MPa/V	637.8 kN/V	-116.1 kN/V	-118.7 kN/V	-0.267 kN/V	REMOVED	REMOVED	180 kN/V	163 kN/V	REMOVED		
19.1	-13.77 MPa/V	637.8 kN/V	-241.5 kN/V	-246.9 kN/V	-0.267 kN/V	REMOVED	REMOVED	180 kN/V	81.4 kN/V	REMOVED		
20.1	-13.77 MPa/V	637.8 kN/V	-116.1 kN/V	-118.7 kN/V	-0.267 kN/V	REMOVED	REMOVED	180 kN/V	81.4 kN/V	REMOVED		
21.1	-13.77 MPa/V	637.8 kN/V	-116.1 kN/V	-118.7 kN/V	-0.267 kN/V	REMOVED	REMOVED	180 kN/V	81.4 kN/V	REMOVED		
22.1	-13.77 MPa/V	637.8 kN/V	-116.1 kN/V	-118.7 kN/V	-0.267 kN/V	REMOVED	REMOVED	180 kN/V	81.4 kN/V	REMOVED		

Note: Sensor sensitivities reduced due to incomplete ice contact as follows:

Sensor	Sensor Length	Ice Thickness	Sensitivity Reduction Factor ^(Thickness in Ice)
EPR 1	2m	0.70m	0.35
EPR 2	2m	0.71m	0.36

* Sensitivity reduced to -246.9 kN/V at 35 min. into test.

SENSOR LABELS

TABLE 10.5

PARAMETER - SENSOR	LABEL	CAL'N FACTOR
<u>Loading System Parameters:</u>		
Hydraulic Line Pressure	HLP	0.0363 MV/V/MPa
Force on Reaction Structure (North Support)-Shear Bar #1	SB1	0.001568 MV/V/KN
Force on Reaction Structure (Centre Support)-Shear Bar sbpp	SB2	0.00276 MV/V/KN
Force on Reaction Structure (South Support)-Shear Bar #3	SB3	0.00270 MV/V/KN
Ram Travel (North Ram)-Ram Travel Potentiometer	RT1	0.267 Meter/V
Ram Travel (South Ram)-Ram Travel Potentiometer	RT2	0.109 Meter/V
<u>Ice-Stress:</u>		
Exxon Production Research (EPR) Panel on Structure	EPR1	1.59 MV/V/MPa
Exxon Production Research Panel in Ice	EPR2	1.71 MV/V/MPa
Canada Marine Eng. Ltd. (CMEL) Sensor - Loc'n #1 - Axis #1	CMEL1	0.040 μ V/V/MPa
Canada Marine Eng. Ltd. (CMEL) Sensor - Loc'n #1 - Axis #2	CMEL2	0.052 μ V/V/MPa
Canada Marine Eng. Ltd. (CMEL) Sensor - Loc'n #1 - Axis #3	CMEL3	0.077 μ V/V/MPa
Canada Marine Eng. Ltd. (CMEL) Sensor - Loc'n #2 - Axis #1	CMEL1	0.032 μ V/V/MPa
Canada Marine Eng. Ltd. (CMEL) Sensor - Loc'n #2 - Axis #2	CMEL2	0.062 μ V/V/MPa
Arctec Canada Limited - Hexpack Sensor - Upper Section	AHX1	1.210 MV/V/MPa
Arctec Canada Limited - Hexpack Sensor - Lower Section	AHX2	1.045 MV/V/MPa
Medof Panel	MDF1	0.746 MV/V/MPa
Weir-Jones Engineering Ltd. - Sensor	WJ1	1.610 MV/V/MPa
Arco Stressmeter - Loc'n #1 - Upper Depth - Axis #1	AR11	0.928 MV/V/MPa
Arco Stressmeter - Loc'n #1 - Upper Depth - Axis #2	AR12	0.940 MV/V/MPa
Arco Stressmeter - Loc'n #1 - Upper Depth - Axis #3	AR13	0.954 MV/V/MPa
Arco Stressmeter - Loc'n #1 - Upper Depth - Axis #4	AR14	0.948 MV/V/MPa
Arco Stressmeter - Loc'n #1 - Lower Depth - Axis #1	AR15	0.969 MV/V/MPa
Arco Stressmeter - Loc'n #1 - Lower Depth - Axis #2	AR16	0.987 MV/V/MPa
Arco Stressmeter - Loc'n #1 - Lower Depth - Axis #3	AR17	0.952 MV/V/MPa
Arco Stressmeter - Loc'n #1 - Lower Depth - Axis #4	AR18	0.916 MV/V/MPa
Arco Stressmeter - Loc'n #2 - Upper Depth - Axis #1	AR21	0.957 MV/V/MPa
Arco Stressmeter - Loc'n #2 - Upper Depth - Axis #2	AR22	0.905 MV/V/MPa
Arco Stressmeter - Loc'n #2 - Upper Depth - Axis #3	AR23	0.999 MV/V/MPa
Arco Stressmeter - Loc'n #2 - Upper Depth - Axis #4	AR24	0.972 MV/V/MPa
Arco Stressmeter - Loc'n #2 - Lower Depth - Axis #1	AR25	0.927 MV/V/MPa
Arco Stressmeter - Loc'n #2 - Lower Depth - Axis #2	AR26	0.933 MV/V/MPa
Arco Stressmeter - Loc'n #2 - Lower Depth - Axis #3	AR27	1.014 MV/V/MPa
Arco Stressmeter - Loc'n #3 - Upper Depth - Axis #1	AR31	0.926 MV/V/MPa
Arco Stressmeter - Loc'n #3 - Upper Depth - Axis #2	AR32	1.016 MV/V/MPa
Arco Stressmeter - Loc'n #3 - Upper Depth - Axis #3	AR33	1.028 MV/V/MPa
Arco Stressmeter - Loc'n #4 - Upper Depth - Axis #1	AR41	0.967 MV/V/MPa
Arco Stressmeter - Loc'n #5 - Upper Depth - Axis #1	AR42	0.967 MV/V/MPa
Arco Stressmeter - Loc'n #6 - Upper Depth - Axis #1	AR43	0.967 MV/V/MPa
Mobil Stressmeter - Loc'n #1	MOBIL1	0.180 μ Strain/KPa
Mobil Stressmeter - Loc'n #2	MOBIL2	0.174 μ Strain/KPa
Mobil Stressmeter - Loc'n #3	MOBIL3	0.816 μ Strain/KPa
IRAD Gauge - Loc'n #1 - Axis #1	IRAD1	0.984
IRAD Gauge - Loc'n #1 - Axis #2	IRAD2	0.920
IRAD Gauge - Loc'n #1 - Axis #3	IRAD3	0.966
<u>Ice Strain</u>		
British Petroleum (BP) Strainmeter - Loc'n 00 - Axis #0	BP000	247.2 μ Strain/V
BP Strainmeters- Loc'n 00 - Axis #1	BP001	238.3 μ Strain/V
BP Strainmeters- Loc'n 00 - Axis #2	BP002	233.0 μ Strain/V
BP Strainmeters- Loc'n 01 - Axis #0	BP010	26.97 μ Strain/V
BP Strainmeters- Loc'n 01 - Axis #1	BP011	23.94 μ Strain/V
BP Strainmeters- Loc'n 01 - Axis #2	BP012	23.31 μ Strain/V
BP Strainmeters- Loc'n 02 - Axis #0	BP020	25.59 μ Strain/V
BP Strainmeters- Loc'n 02 - Axis #1	BP021	21.98 μ Strain/V
BP Strainmeters- Loc'n 02 - Axis #2	BP022	21.03 μ Strain/V
BP Strainmeters- Loc'n 03 - Axis #0	BP030	26.66 μ Strain/V
BP Strainmeters- Loc'n 03 - Axis #1	BP031	25.21 μ Strain/V
BP Strainmeters- Loc'n 03 - Axis #2	BP032	23.07 μ Strain/V
BP Strainmeters- Loc'n 04 - Axis #0	BP040	24.08 μ Strain/V
BP Strainmeters- Loc'n 04 - Axis #1	BP041	22.56 μ Strain/V
BP Strainmeters- Loc'n 04 - Axis #2	BP042	24.75 μ Strain/V

NOTES: 1. These are gauge factors. The ice stress is determined by using the gauge factor to calculate the strain in the vibrating wire and then by relating it to the hydrostatic calibration.

2. The locations of the above strainmeter sites are shown on Figure 5 and are related to the adopted sensor labels as follows:

Strainmeter site Location Shown on Figure 5	Labels of Strainmeters at Site
BP1	BP000; BP001; BP002
BP2	BP030; BP031; BP032
BP3	BP010; BP011; BP012
BP4	BP020; BP021; BP022
BP5	BP040; BP041; BP042

TABLE 10.6

TEST NO.	INT. NO.	LOAD (kN)	NOM. PRES. (MPa)	sensor pressures			
				M01	M1	M02	M03
4	1	51.0	23.9	5.9	19.3	15.6	27.6
	2	157.0	73.7	21.9	52.0	40.7	69.4
5	1	158.3	74.3	19.0	41.1	31.0	67.4
	2	300.6	141.1	42.7	103.4	61.7	125.8
6	1	419.1	196.7	61.4	140.4	72.3	166.8
	2	505.5	237.3	83.8	166.2	88.0	200.6
	3	681.0	319.7	123.8	215.2	144.0	280.7
7	1	42.5	20.0	5.2	0.82	1.4	5.6
	2	295.8	138.9	47.9	61.0	53.1	98.1
8	1	145.4	68.3	20.9	26.2	25.2	45.9
	2	224.3	105.3	34.0	36.7	40.0	77.1
9	1	678.0	318.3	138.6	300.4	222.0	220.4
	2	21.3	10.0	93.0	88.1	111.1	113.4
	3	21.3	10.0	30.4	17.1	4.0	14.8
	4	22.8	10.7	18.2	8.9	-3.0	6.7
10	1	623.6	292.8	108.1	160.7	158.4	181.1
	2	878.2	412.3	157.9	249.0	279.4	256.7
	3	981.0	460.5	181.7	269.5	325.4	284.6
11	1	995.6	467.4	186.8	299.4	371.4	235.3
12	1	256.2	120.3	21.7	22.1	15.5	27.6
	2	473.4	222.2	47.8	44.4	30.6	49.3
	3	539.4	253.2	54.6	54.0	33.1	54.1
13	1	314.7	147.7	61.7	70.5	52.9	67.1
	2	349.2	163.9	72.9	93.4	80.2	83.2
	3	1198.6	562.7	253.8	317.1	280.5	266.2
14	1	495.5	232.6	119.1	176.2	186.2	121.9
	2	712.1	334.3	162.0	206.6	186.2	147.2
15	1	583.3	273.8	116.4	152.6	165.5	114.8
	2	1158.3	543.8	214.4	315.6	339.6	224.4
	3	1386.2	650.8	292.2	393.0	348.6	260.6
16	1	629.9	295.7	148.6	181.3	188.9	126.7
	2	858.3	402.9	196.9	267.3	255.8	157.8
17	1	257.6	120.9	42.6	43.6	39.2	34.8
	2	470.2	220.7	89.4	91.5	75.2	89.1
	3	462.3	217.0	97.0	105.5	104.8	95.3
18	1	523.6	245.8	91.7	111.0	110.7	71.7
	2	722.9	339.3	162.2	225.5	239.6	150.4
	3	1044.7	490.4	229.8	335.2	296.1	195.2
19	1	429.5	210.6	93.6	122.8	132.5	72.1
	2	1017.7	477.8	212.7	300.8	303.6	204.2
	3	1218.2	572.1	298.0	403.3	303.8	224.2
20	1	151.9	71.3	35.2	28.7	30.7	15.3
	2	267.4	125.5	65.1	52.2	55.4	30.0
	3	422.3	198.3	113.7	94.2	90.2	63.4
21	1	243.9	114.5	38.7	52.0	23.6	32.4
	2	409.0	192.0	117.0	96.2	29.4	71.0
	3	543.2	254.5	165.3	130.4	34.8	114.9
	4	713.7	335.1	217.2	219.0	38.7	186.9
22	1	146.1	68.6	23.3	26.7	10.0	27.3
	2	258.2	118.9	38.9	68.3	14.6	36.6
	3	385.7	181.1	110.6	109.0	17.0	94.1
	4	528.5	248.1	153.0	150.6	18.4	133.8
	5	657.2	308.5	204.4	188.5	20.0	176.0
	6	788.8	370.3	246.0	226.6	21.5	217.1
	7	911.1	427.7	292.4	267.8	22.9	242.9
	8	979.7	459.9	344.2	324.5	24.7	285.3
	9	104.2	565.3	388.6	373.8	26.6	325.7
	10	345.8	631.8	440.6	424.3	29.8	362.5

SENSOR RESULTS

Load
Structure Width (taken as 3.05 m) x Ice Thick (taken as 0.7 m)

2. Abbreviations Used: S.R. - Sensor Removed from data acquisition system.

N.I. - Sensor Not Installed.

N.D. - No Data obtained.

3. Tabulated sensor pressures are mean values recorded by sensor over indicated test intervals (TEST INT.).

4. See text for definition of sensor acronyms.

TABLE 10.7

Stress Ratios From F.E. Analyses

Sensor	<u>F.E. Stress</u> <u>Nominal Stress</u>					Mean
	Test9(1.0)	Test15(2.0)	Test15(3.0)	Test19(2)	Test19(3)	
EPR 1	0.75	0.82	0.88	0.90	0.98	0.87
ARCO 1	0.87	0.91	1.00	0.88	1.05	0.94
Mobil 2	0.68	0.73	0.74	0.75	0.75	0.73
CMEL MK IV-C	0.62	0.60	0.54	0.59	0.49	0.57
MFDOF	0.68	0.71	0.75	0.71	0.80	0.73
WJ 1	0.53	0.55	0.49	0.55	0.47	0.52
HEXPACK	0.56	0.56	0.58	0.57	0.58	0.57
AR-42/43	0.56	0.56	0.61	0.58	0.63	0.59
Mobil 1	0.48	0.51	0.51	0.50	0.52	0.50
ARCO 2	0.50	0.52	0.50	0.50	0.52	0.51
EXXON 2	0.39	0.42	0.43	0.41	0.42	0.41
MOBIL 3	0.36	0.36	0.38	0.37	0.40	0.37
ARCO 3	0.34	0.35	0.33	0.31	0.31	0.33
IRAD	0.47	0.45	0.43	0.45	0.41	0.44
ARCO 4-2,3	0.56	0.56	0.62	0.57	0.63	0.59

NOTE: The variation in factors between sensors is related to the physical location of the sensors in the ice sheet and not to actual sensor outputs displayed during the tests.

TABLE 10.8

SENSOR: WJ1: THICKNESS AT SENSOR 60 cm.
PRESSURE ON STRUCTURE REFERENCED TO 70 cm.

Test No.	Test Interval	Stress Factor Based On F.E. Analysis	Sensor Reading (kPa)	Ice Pressure On Structure Based On Sensor Reading (kPa)	Corrected For Thickness Variation (kPa)	Actual Nominal Ice Pressure On Structure (kPa)	Difference	Test Time (of intervals) (mins)	Remarks
4	1	0.63	19.3	30.6	26.2	23.9	+ 9.6	2.1	
4	2	0.63	52.0	82.5	71.0	73.7	- 3.7	2.8	
5	1	0.63	41.1	65.24	56.0	74.3	-25.0	6.6	
5	2	0.63	103.4	164.13	141.0	141.1	0	17.6	
6	1	0.63	215.2	342.0	294.0	320.0	- 8.0	3.0	
7	1	0.52	61.0	17.3	100.9	139.0	-27.3	2.7	
8	1	0.52	26.2	50.4	43.3	68.3	-36.6	0.17	
9	1	0.53	200.4	378.4	325.2	318.3	+ 2.2	155.25	
9	2	0.52	88.1	169.4	145.7	160.6	- 9.3	10.75	
10	1	0.52	299.4	518.3	445.7	460.5	- 3.2	1.3	
11	1	0.52	299.4	575.8	495.2	467.4	+ 5.9	9.73	Problems With Load Hydraulics Discount this Test.
12	1	0.52	54.0	103.9	89.4	251.2	-65.0	1.05	
13	1	0.52	317.1	609.8	524.4	582.7	-58.6	1.5	
14	1	0.52	176.2	338.9	291.5	232.6	+25.3	52.25	
14	2	0.52	206.6	397.3	342.0	334.3	+ 2.3	17.08	
15	1	0.49	393.0	802.0	689.7	650.8	+ 6.0	0.6	
16	1	0.52	181.3	348.7	299.9	295.7	+ 1.4	15.6	
16	2	0.52	267.3	514.0	442.0	402.9	+ 9.7	24.0	
17	1	0.52	43.6	83.9	72.0	121.0	-40.5	8.85	
17	3	0.52	105.5	202.9	175.0	217.0	-15.4	1.95	
18	1	0.52	335.2	644.6	554.0	490.4	+14.9	1.65	
19	2	0.55	330.8	601.5	517.3	477.8	+ 8.3	0.9	
19	3	0.47	403.3	858.0	738.0	572.0	+29.0	1.5	

Average % Difference 13.3%

TABLE 10.9

SLOT TEST: PREDICTED VERSUS
MEASURED STRESS WJ 1-Inter-
pretation "A" (Allowing
for Crack)

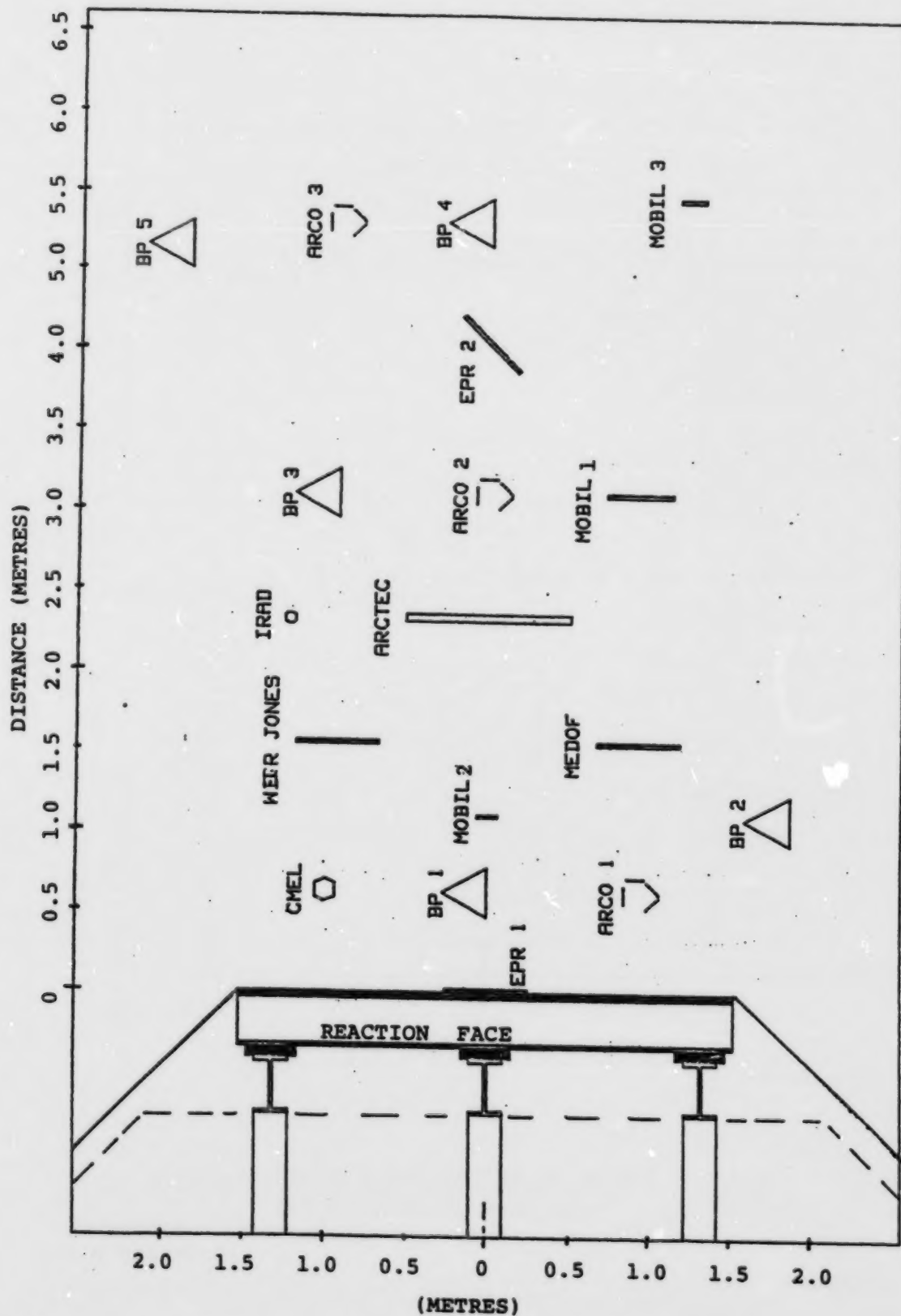
Test No.	Test Interval	Predicted Stress at Sensor Location Based on Load Cell Readings (kPa)	Actual Sensor Reading (kPa)
20	1	63	29
	2	100	52
	3	138	94
21	1	97	52
	2	122	96
	3	144	150
	4	207	219
22	1	99	37
	2	98	68
	3	91	109
	4	106	151
	5	106	188
	6	106	227
	7	111	268
	8	132	325
	9	167	373
	10	199	424

TABLE 10.10

SLOT TEST: PREDICTED VERSUS MEASURED STRESS

WJ 1- INTERPRETATION B (IGNORING CRACK)

Test No.	Test Interval	Predicted Stress at Sensor location Based on Load Cell Readings (kPa)	Actual Sensor Reading (kPa)
20	1	71	29
	2	125	52
	3	198	94
21	1	115	52
	2	192	96
	3	254	150
	4	335	219
22	1	68	37
	2	119	68
	3	181	109
	4	248	151
	5	308	188
	6	370	227
	7	428	268
	8	460	325
	9	565	373
	10	632	424



Main Instrumentation Comparison Area

FIGURE 40

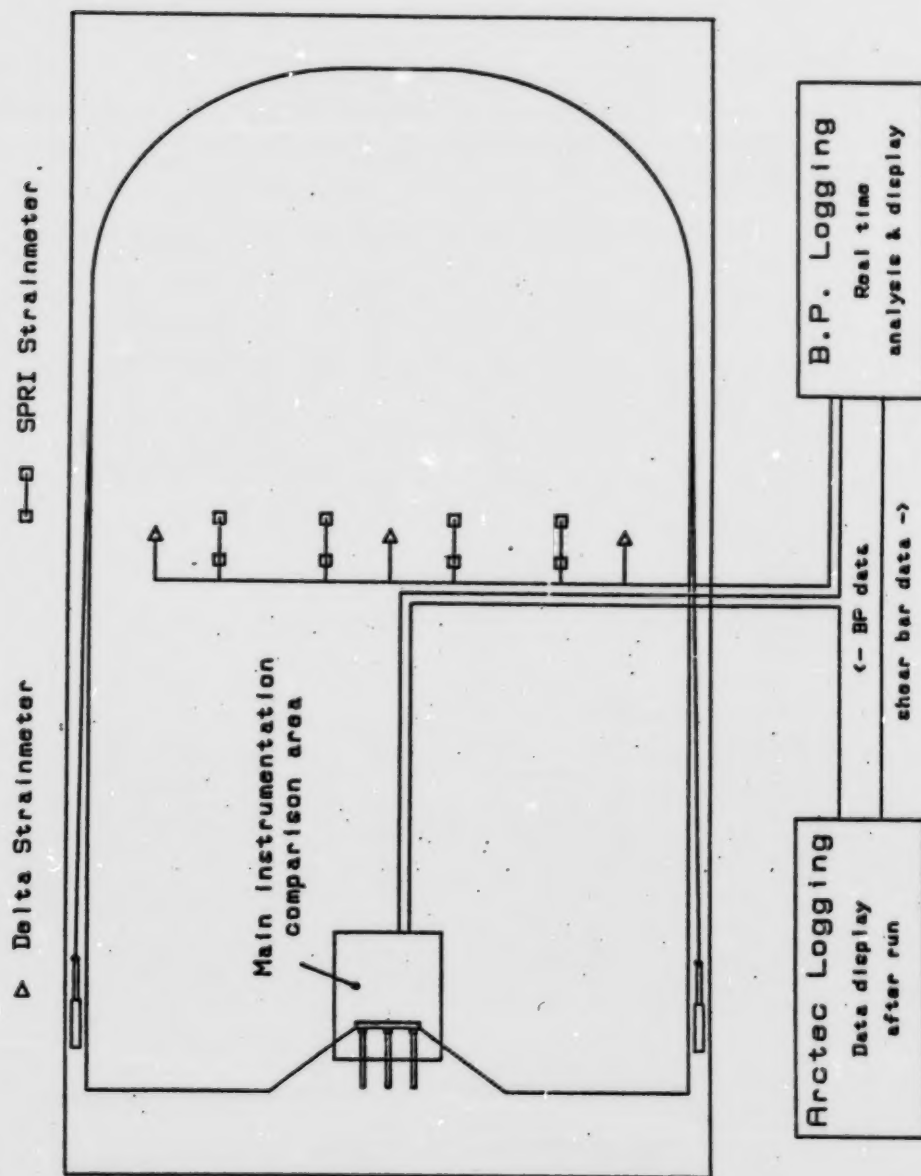
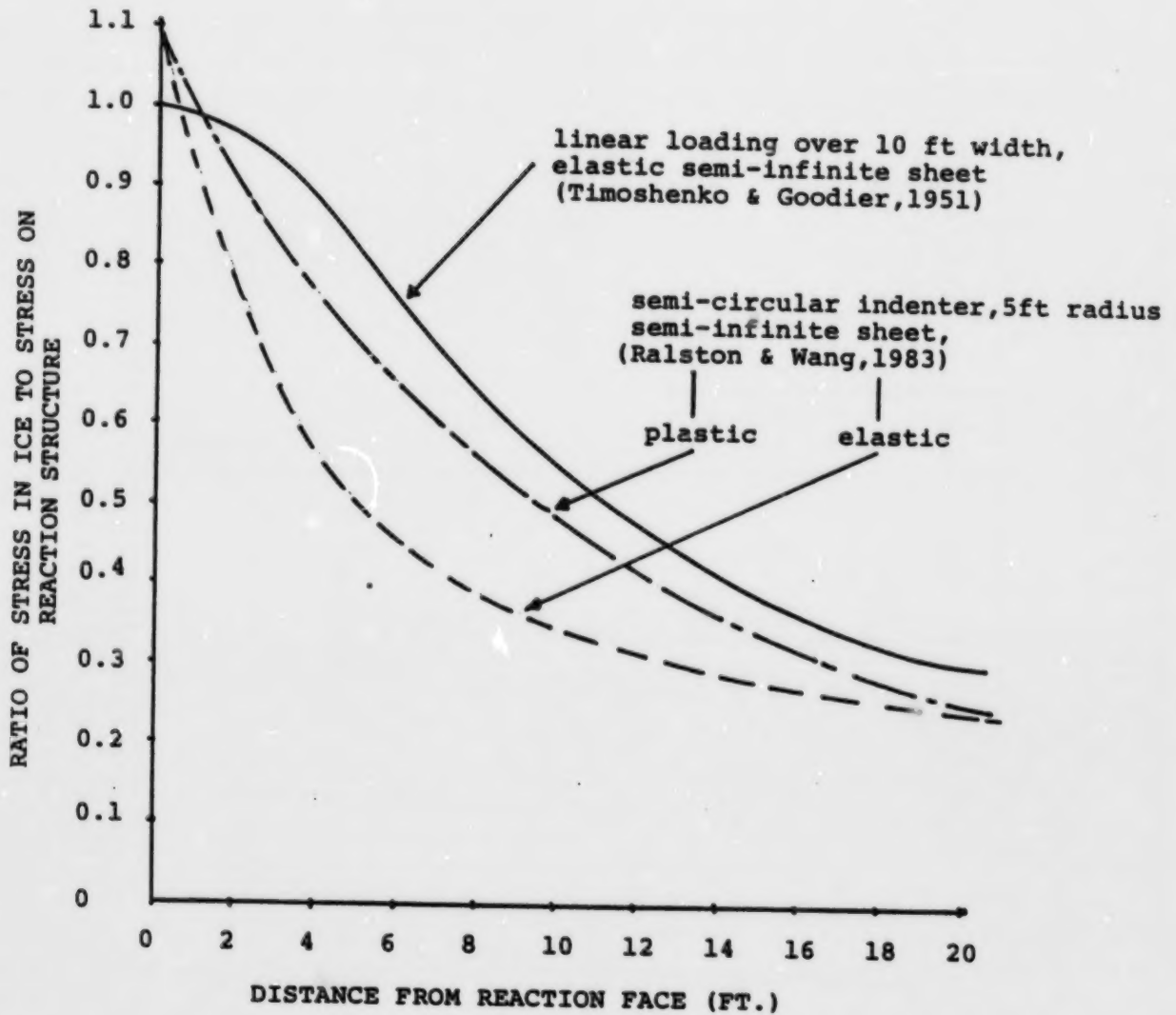


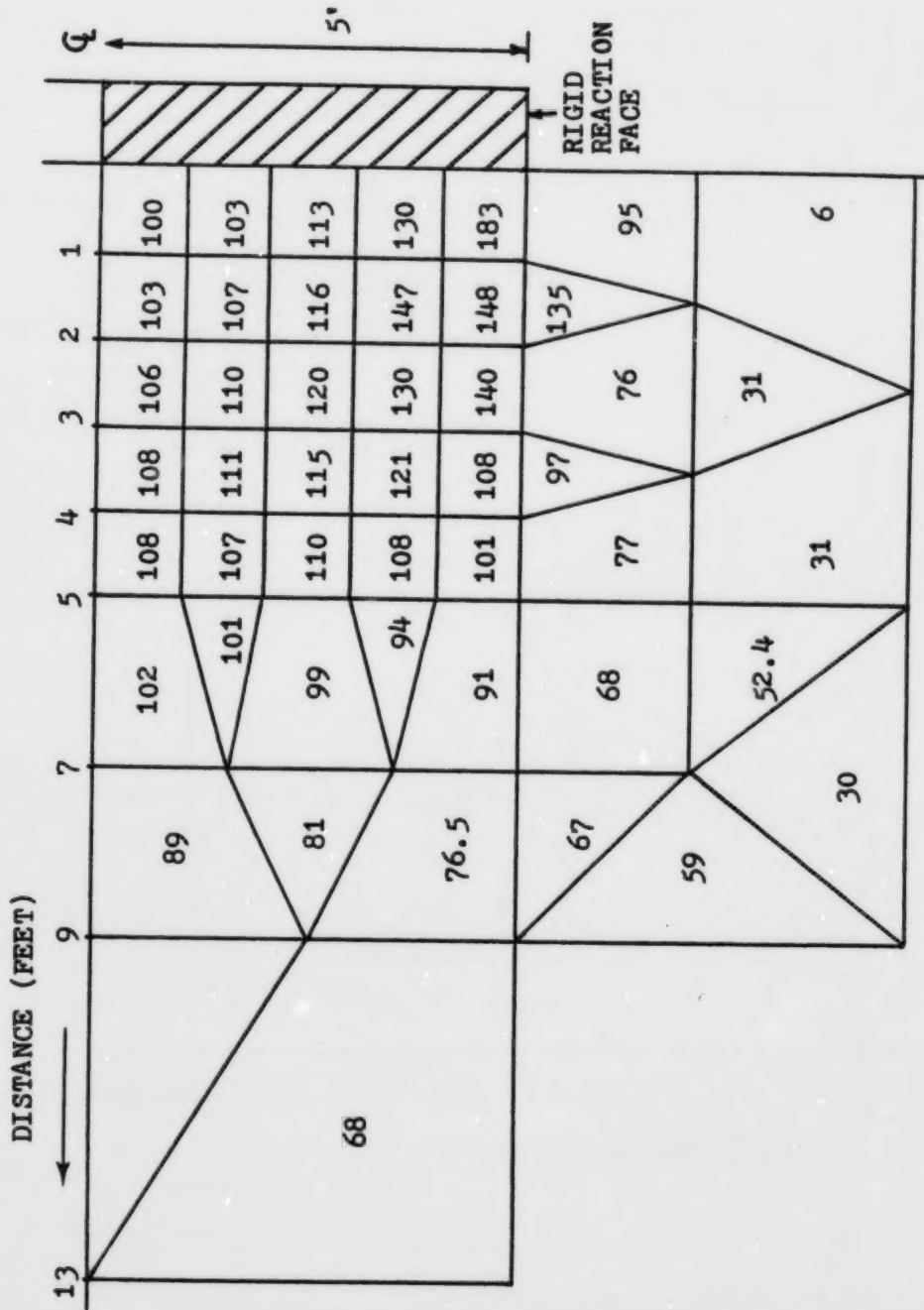
FIGURE 49
(Courtesy B.P.)

General Instrumentation Layout and Logging



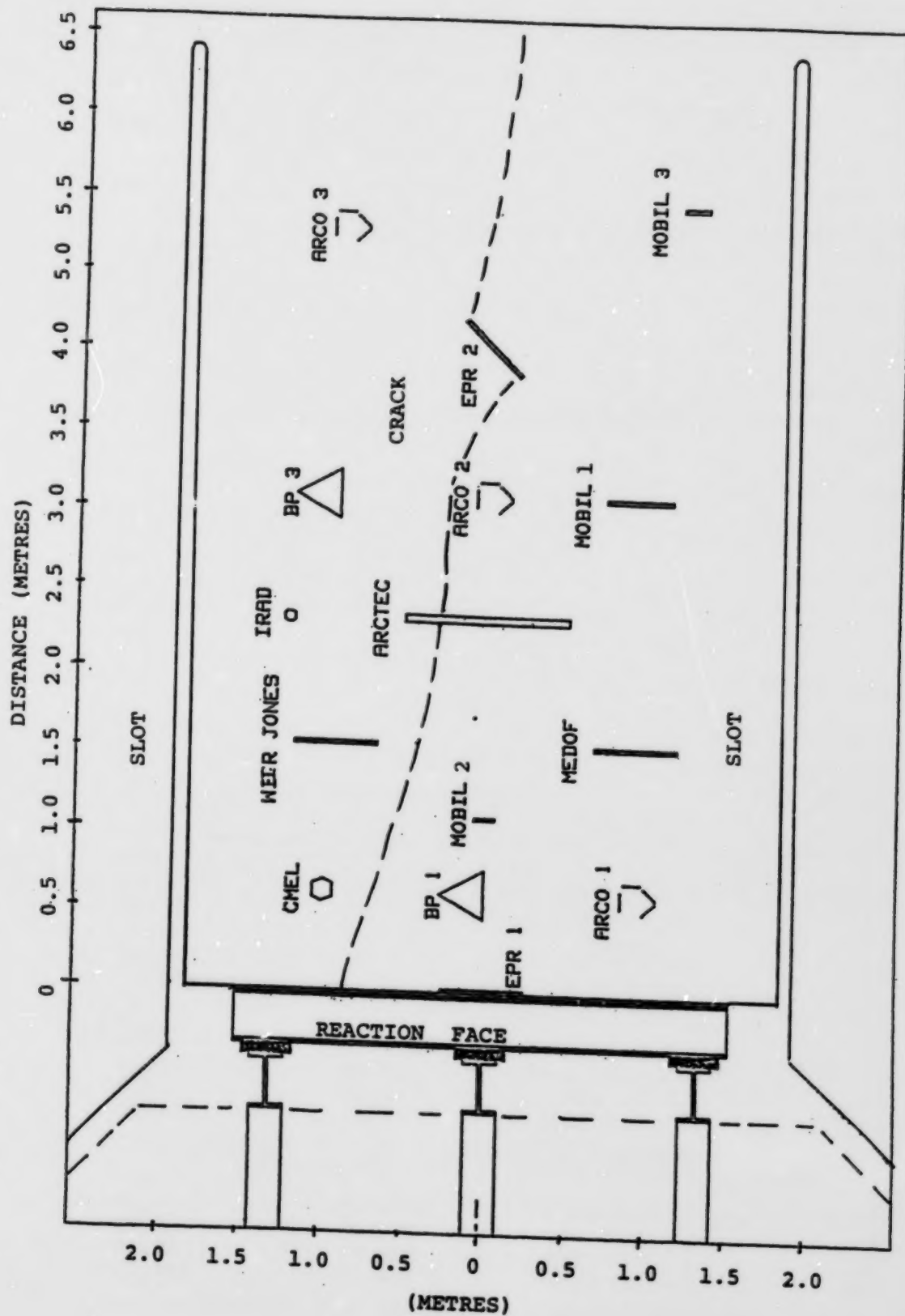
STRESS DECAY ALONG CENTRE-LINE OF ICE SHEET
(By analytical methods)

FIGURE 50



CALCULATED ELASTIC STRESS DISTRIBUTION (PSI)
 (SYMMETRICAL LOADING)
 20" ICE: 400 KIPS TOTAL LOAD: $E_{ICE} = 10^6$ (PSI)

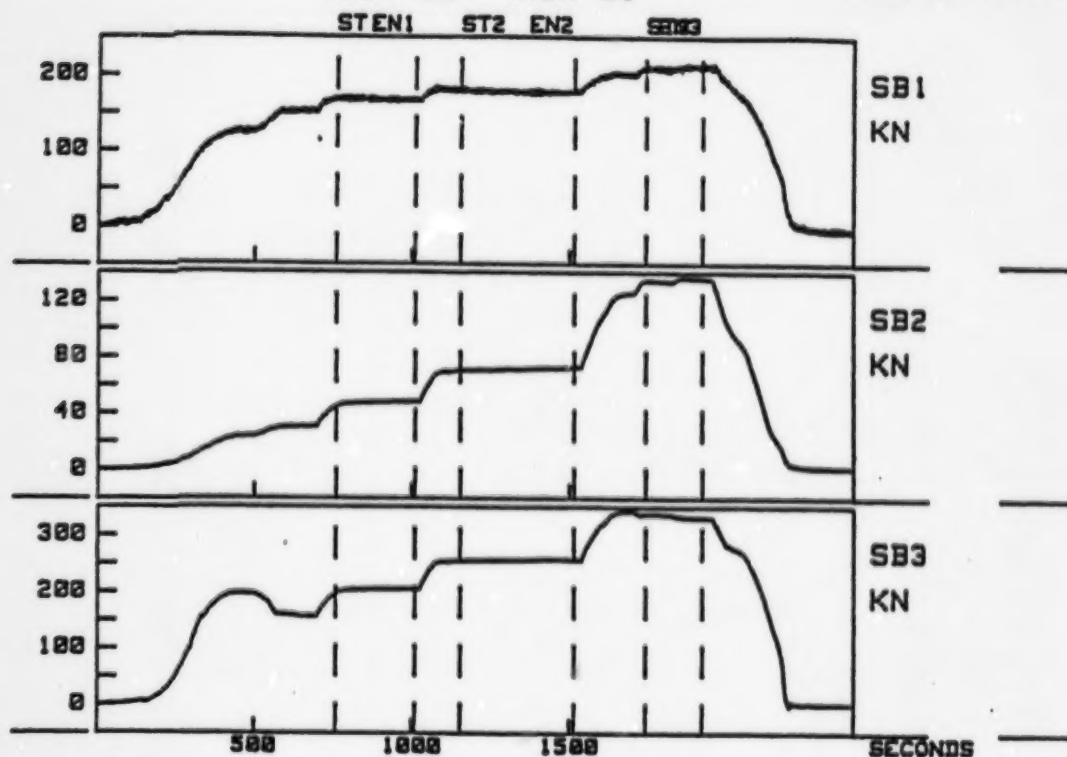
FIGURE 51



CONFIGURATION FOR THE SLOT TESTS (20, 21, & 22)

FIGURE 52

1830C-LOAD SENSORS EVALUATION - SHEAR BAR (LOAD CELL)
TEST 06 RUN 01
READINGS VS. TIME



DATA DIGITIZED ON: 06 MAR 1983
DIGITIZING RATE: 1 Hz/CHANNEL
FILTER FREQUENCY: 400 HZ

INTERVAL STATISTICS

INTERVAL 1 START: 757 END: 1009 SECONDS

CHANNEL	MINIMUM	MAXIMUM	MEAN VALUE	STAN. DEV.
SB1	163.24	171.03	167.26	1.69
SB2	44.516	48.41	47.374	.748
SB3	197.68	205.82	204.38	1.61

INTERVAL 2 START: 1153 END: 1513 SECONDS

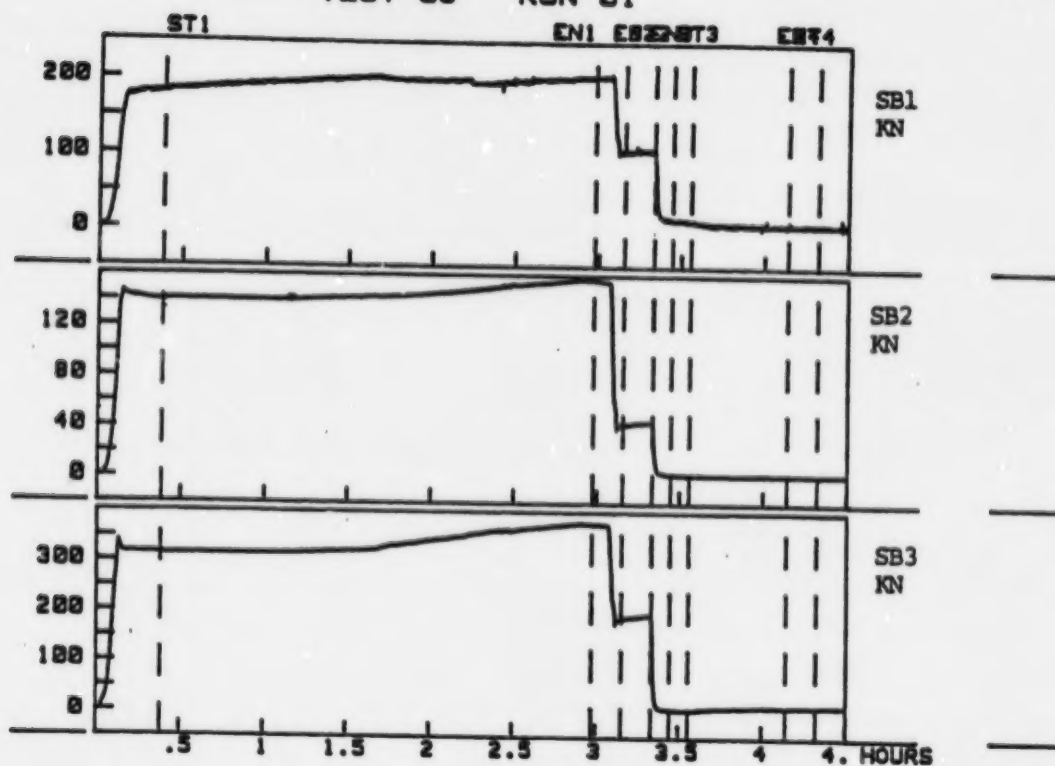
CHANNEL	MINIMUM	MAXIMUM	MEAN VALUE	STAN. DEV.
SB1	174.14	183.49	177.99	1.46
SB2	70.004	73.013	71.469	.618
SB3	253.75	257.82	256.05	.816

INTERVAL 3 START: 1741 END: 1921 SECONDS

CHANNEL	MINIMUM	MAXIMUM	MEAN VALUE	STAN. DEV.
SB1	205.29	216.2	211.13	2.04
SB2	133.37	136.91	135.19	1.2
SB3	330.159	338.75	334.713	2.78

FIGURE 53

1830C-LOAD SENSORS EVALUATION - SHEAR BAR READINGS
TEST 09 RUN 01



1830C-LOAD SENSORS EVALUATION - ARCTEC HEXPACK (AHX)
TEST 09 RUN 01 AND MEDOF PANEL (MDF)

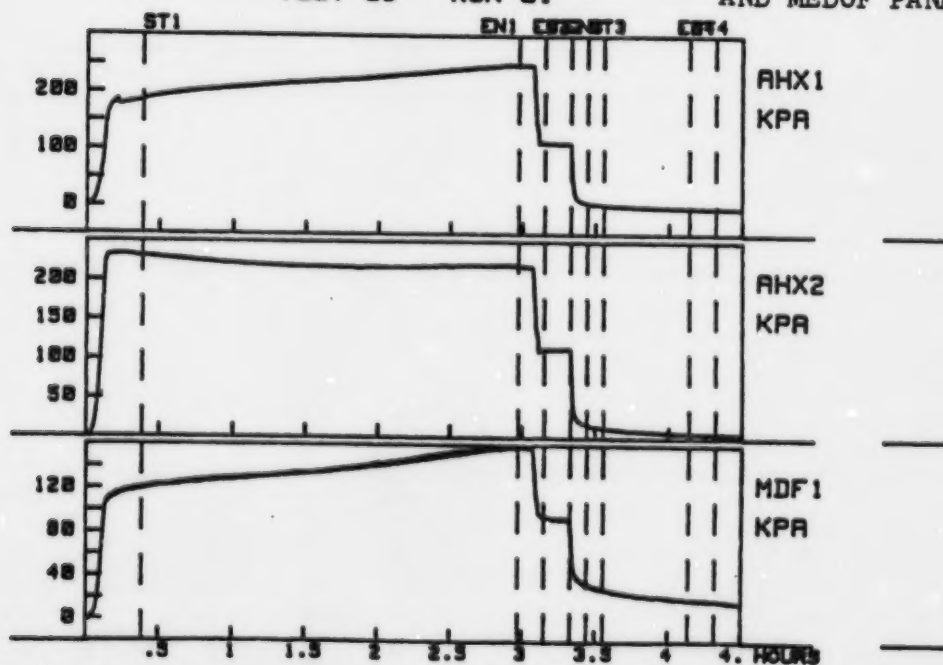


FIGURE 54

1830C-LOAD SENSORS EVALUATION - HYDRAULIC PRESSURE
TEST 09 RUN 01 AND RAM STROKES

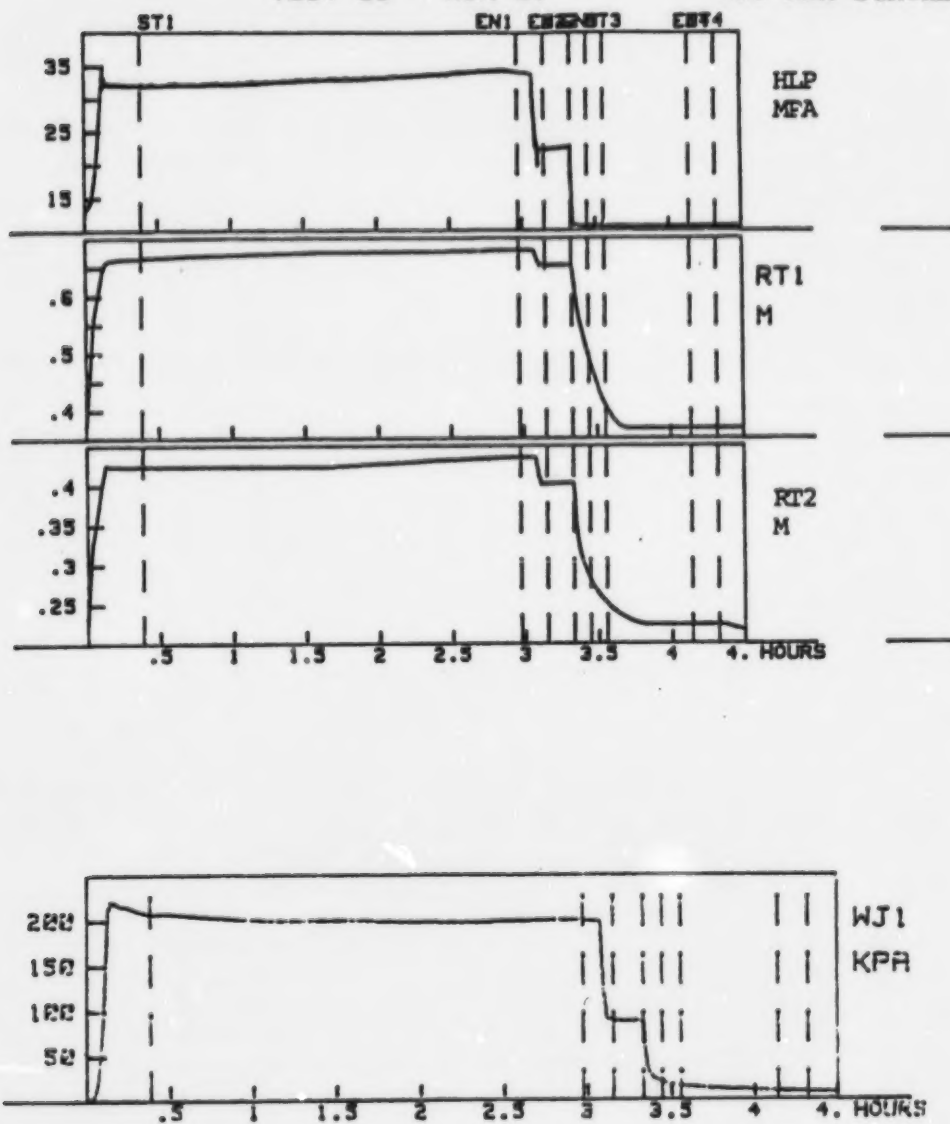
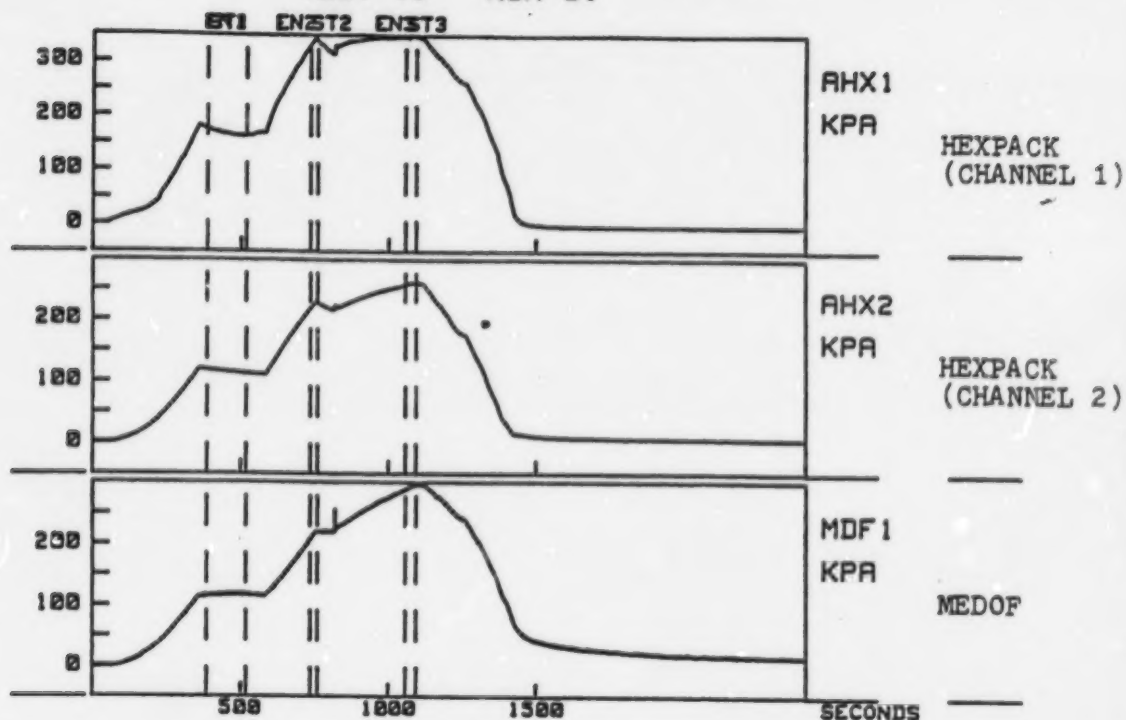


FIGURE 55

1830C-LOAD SENSORS EVALUATION TEST 15 RUN 01



1830C-LOAD SENSORS EVALUATION TEST 15 RUN 01

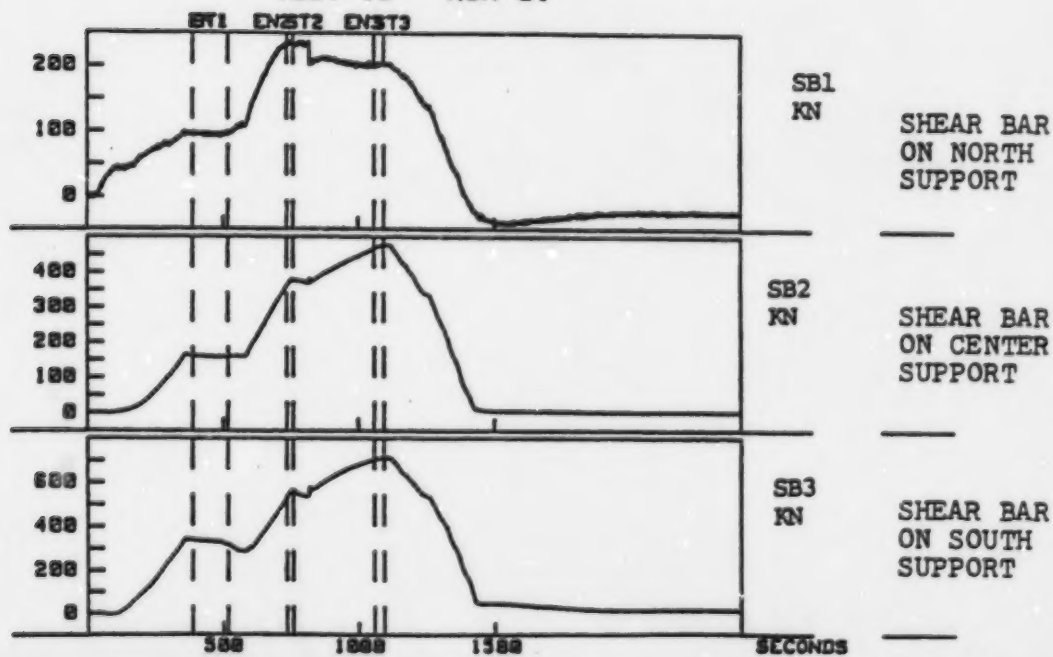


FIGURE 56

1830C-LOAD SENSORS EVALUATION
TEST 15 RUN 01

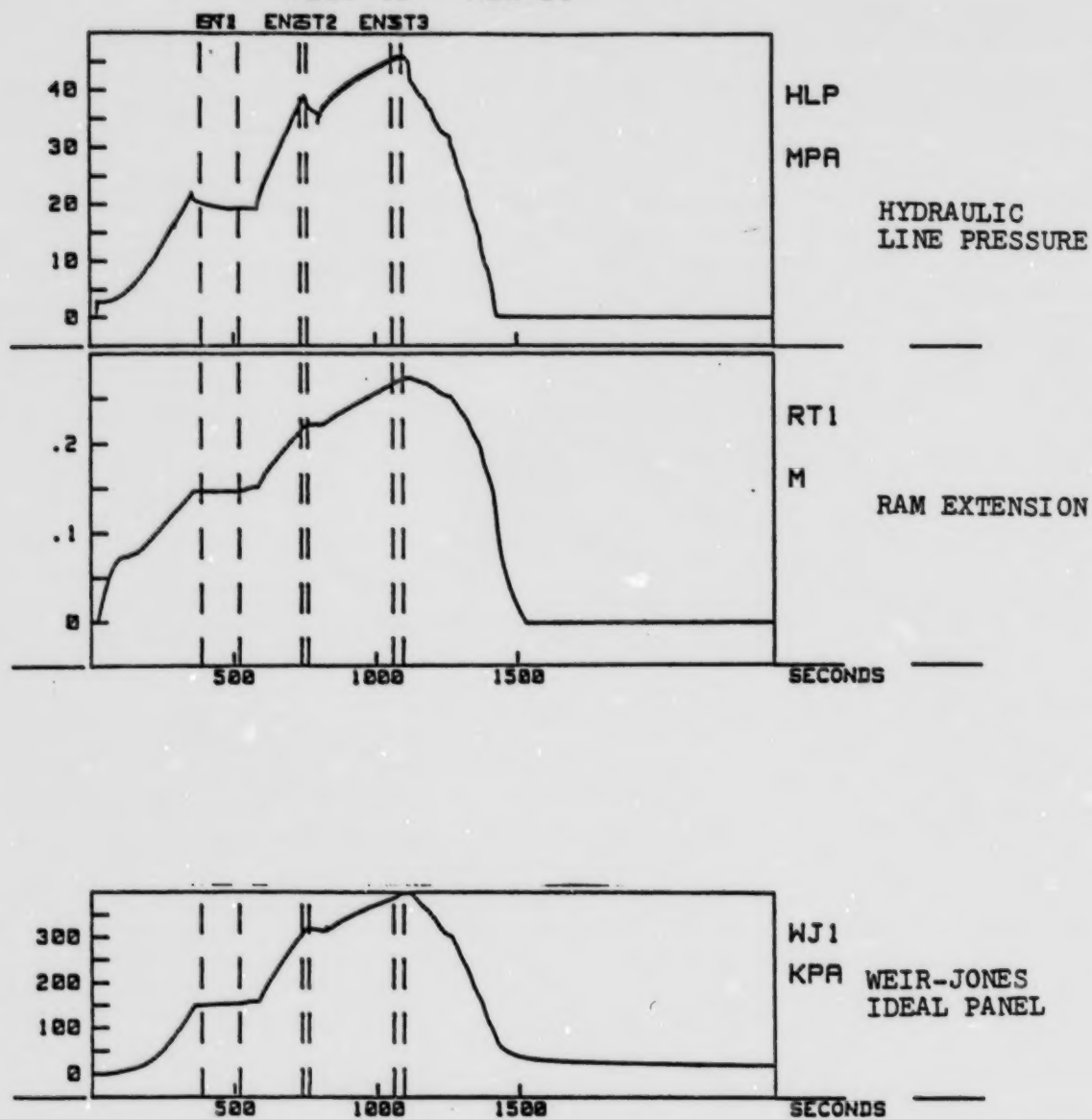


FIGURE 57

ARCTEC CANADA LIMITED

PREDICTED STRESS CONTOURS

Comp. Stress in Y Direction (kPa)

Actual sensor readings in ()

TEST: 9

TEST INTERVAL: 1

5 4 3 2 1 0 1 2 3 4 5 feet

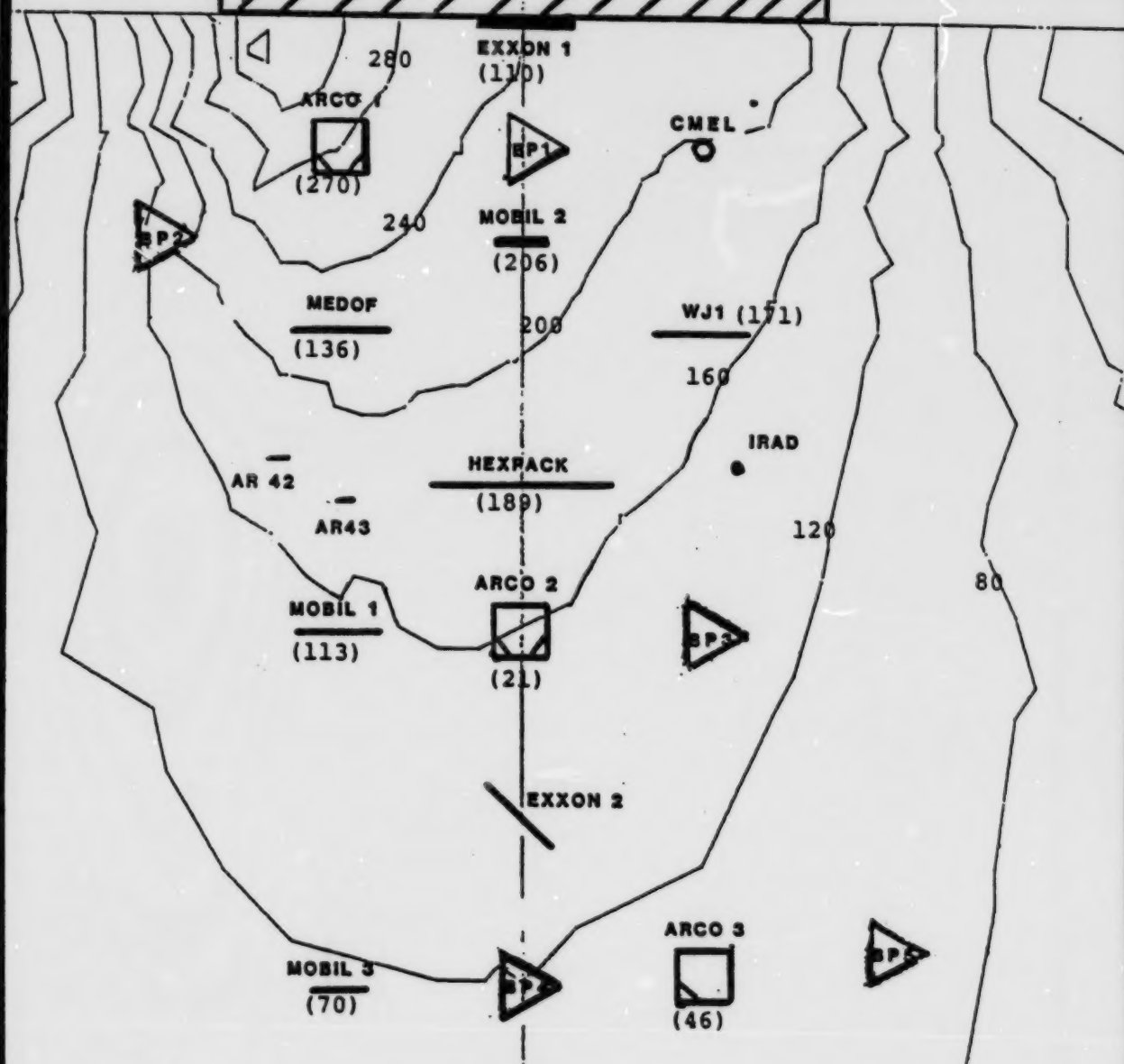
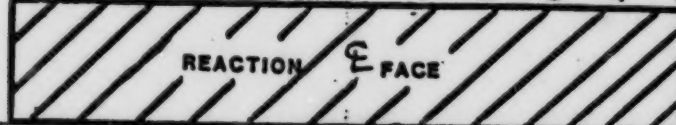
Y
↑

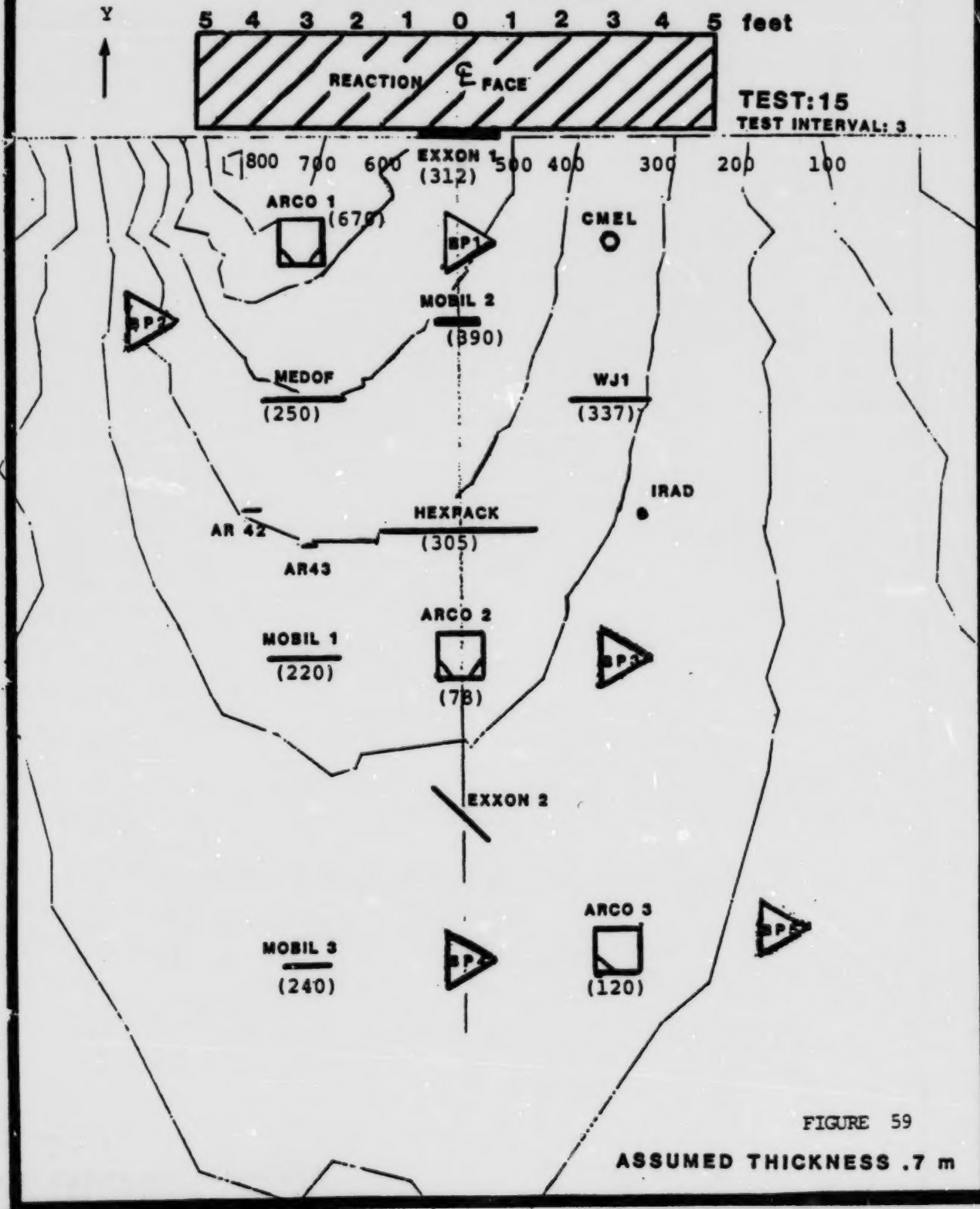
FIGURE 58

ASSUMED THICKNESS .7 m

PREDICTED STRESS CONTOURS

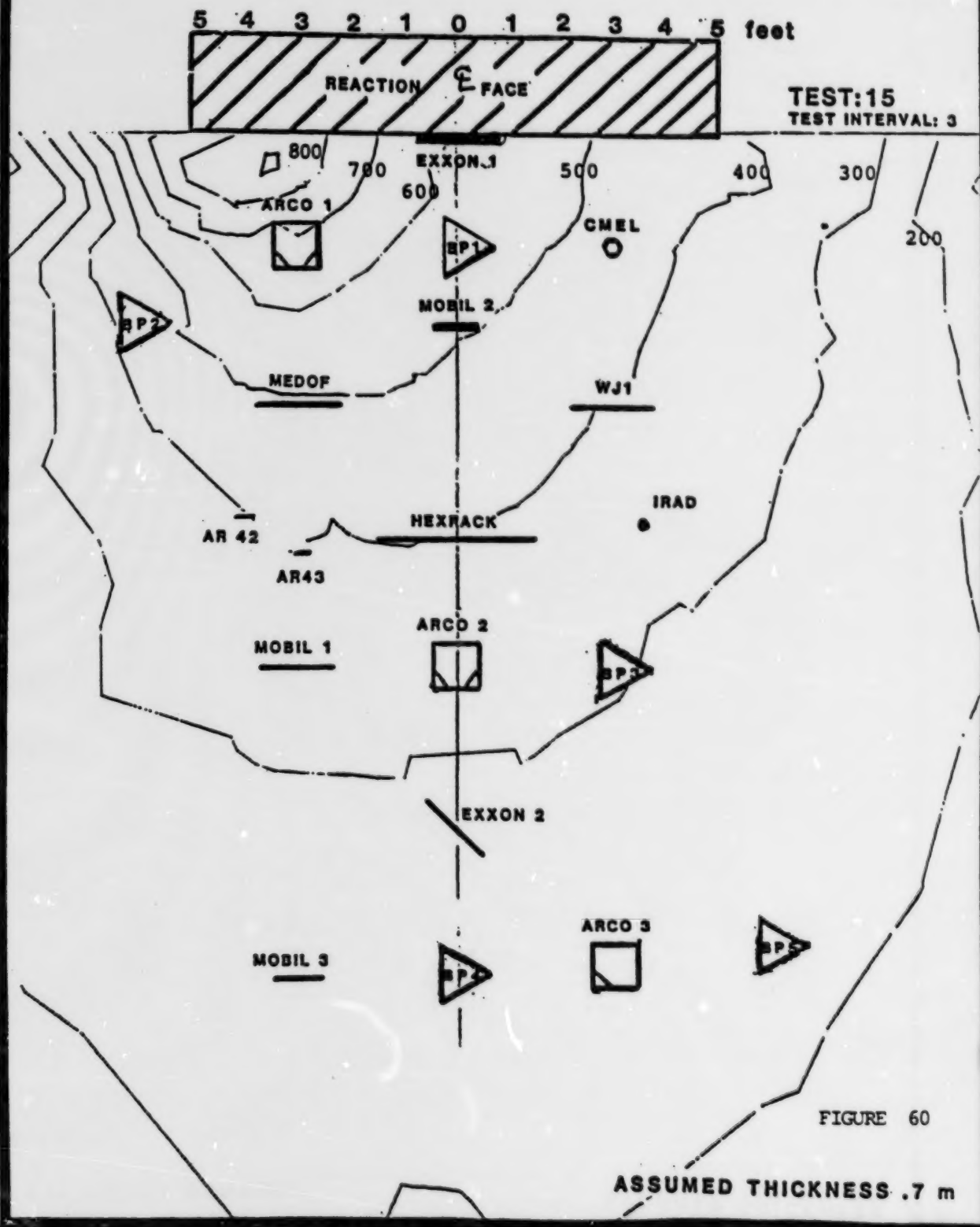
Comp. Stress in Y-Direction (kPa)

Actual sensor readings shown in ()



PREDICTED STRESS CONTOURS

Max. Principal Comp. Stress (kPa)



PREDICTED STRESS CONTOURS

Min. Principal Comp. Stress (kPa)

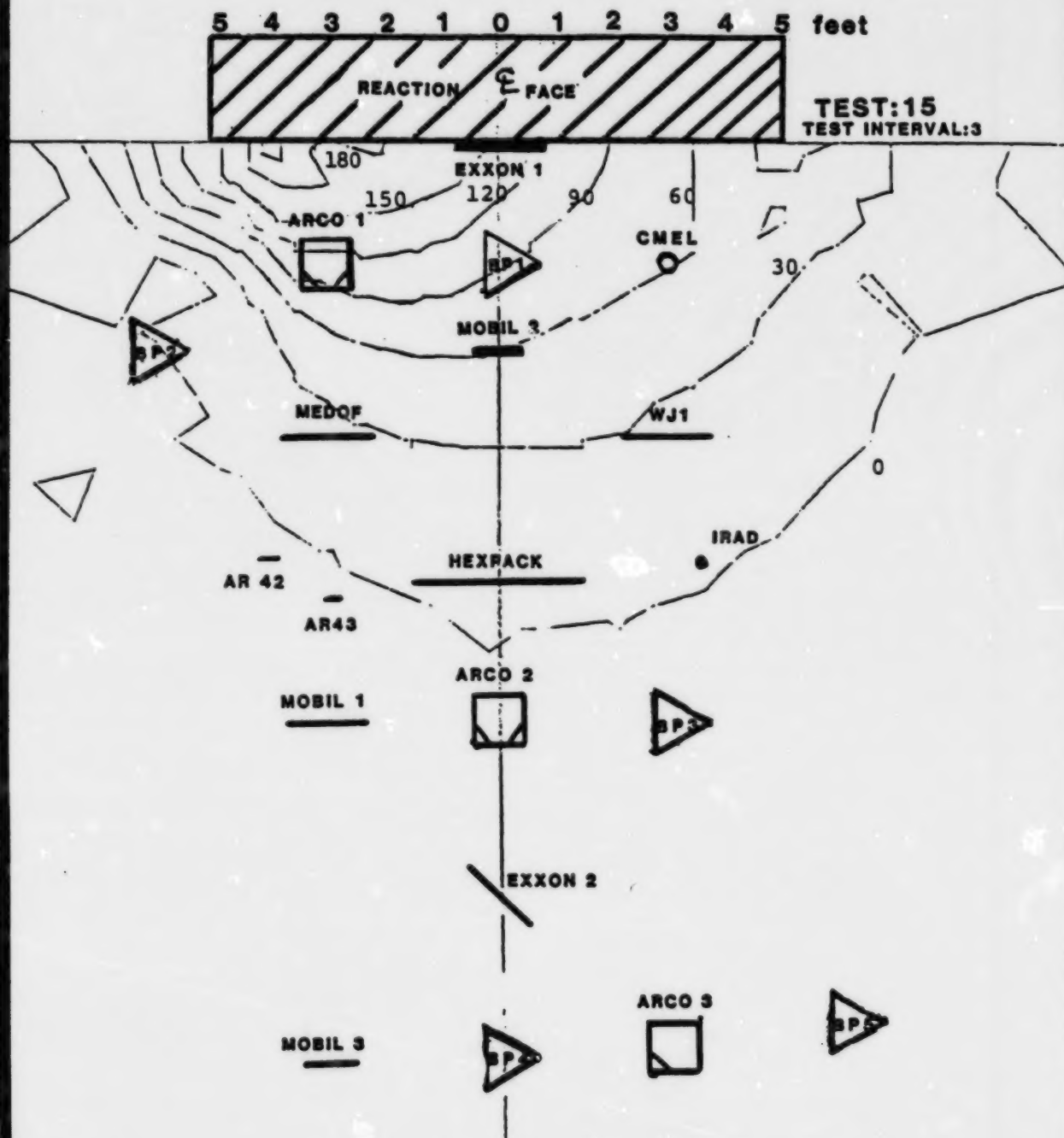
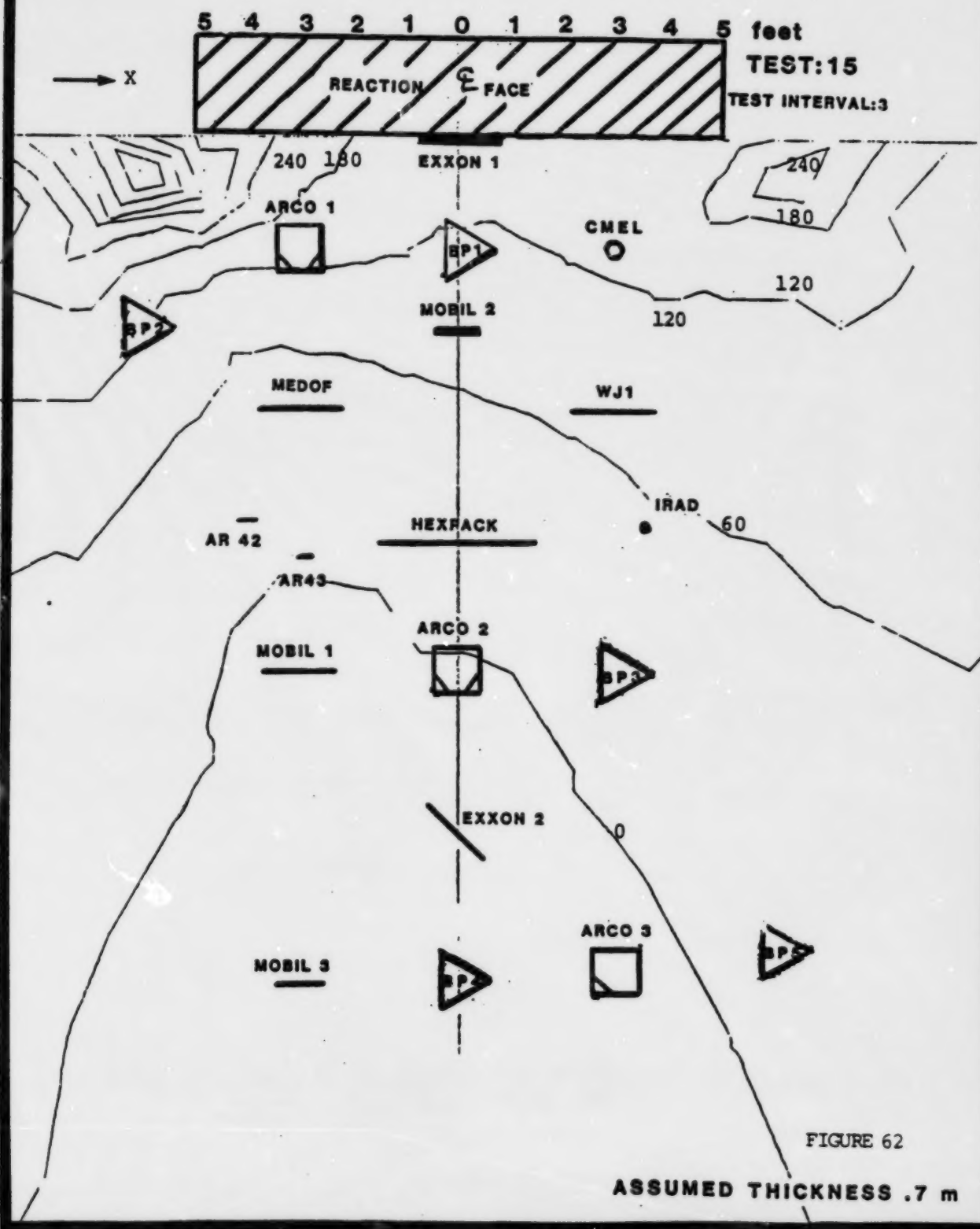


FIGURE 61

ASSUMED THICKNESS .7 m

PREDICTED STRESS CONTOURS

Comp. Stress in X Direction (kPa)



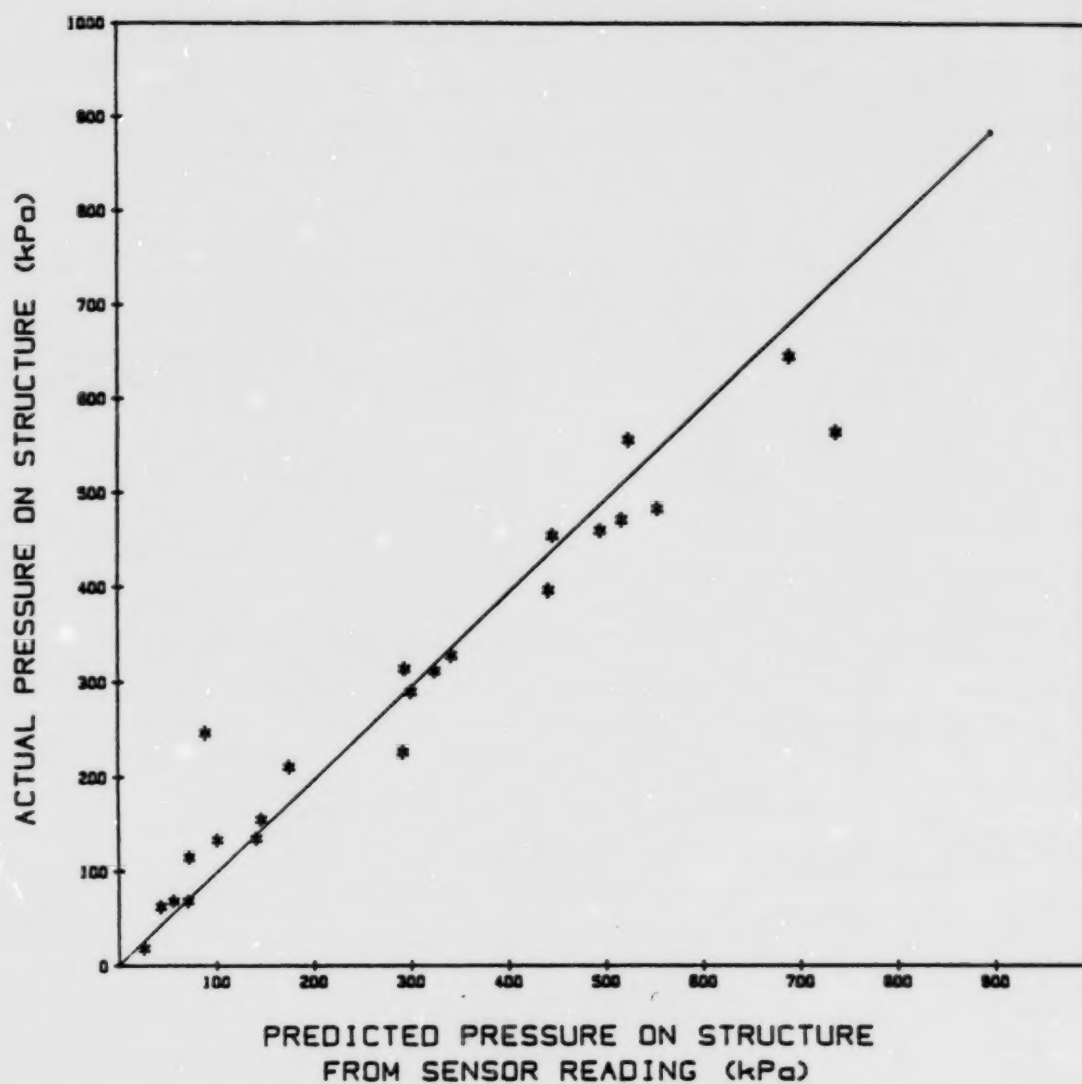


FIGURE 63 RESULTS OF UNSLOTTED TESTS
SENSOR: WEIR-JONES IDEAL PANEL

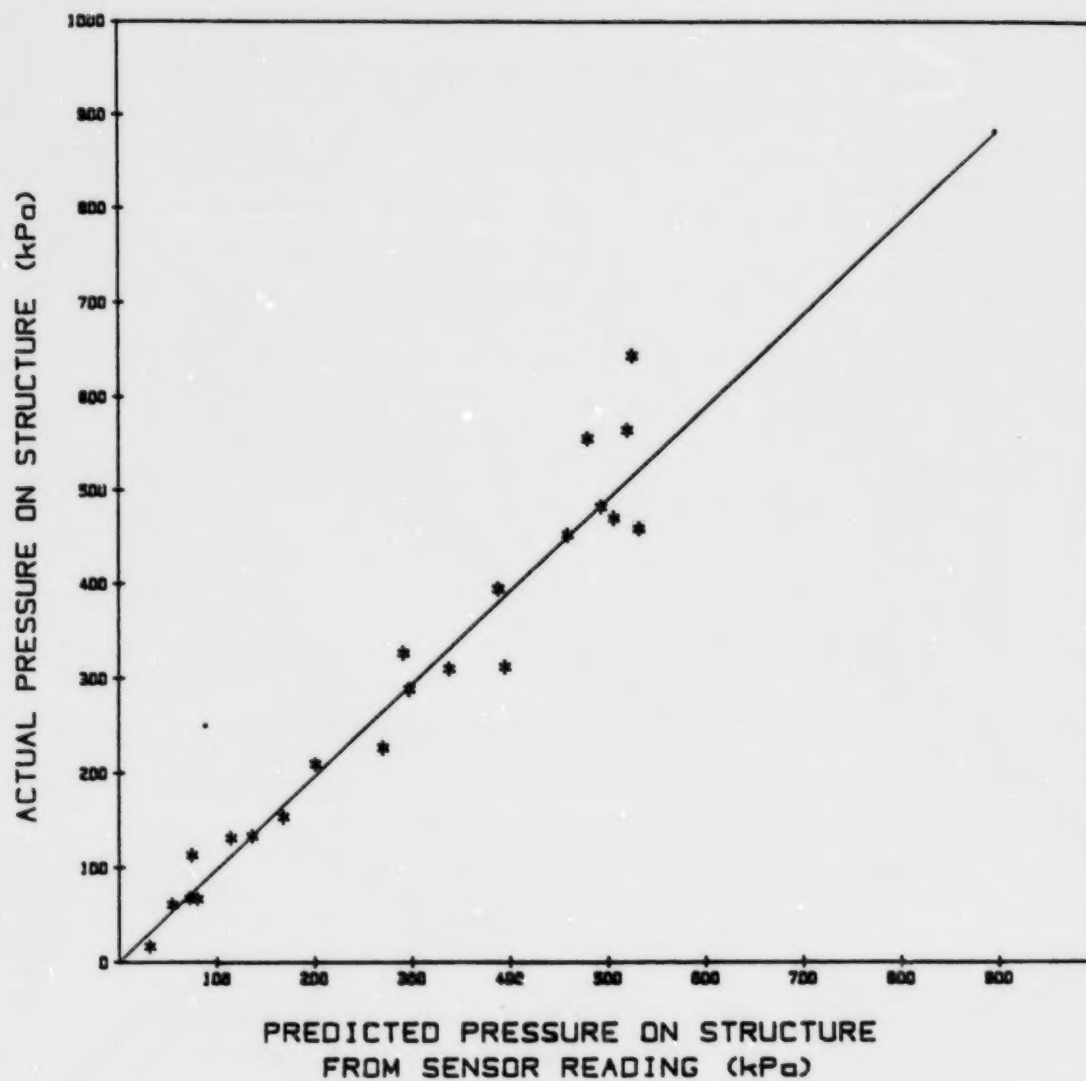


FIGURE 64 RESULTS OF UNSLOTTED TESTS
SENSOR: HEXPACK

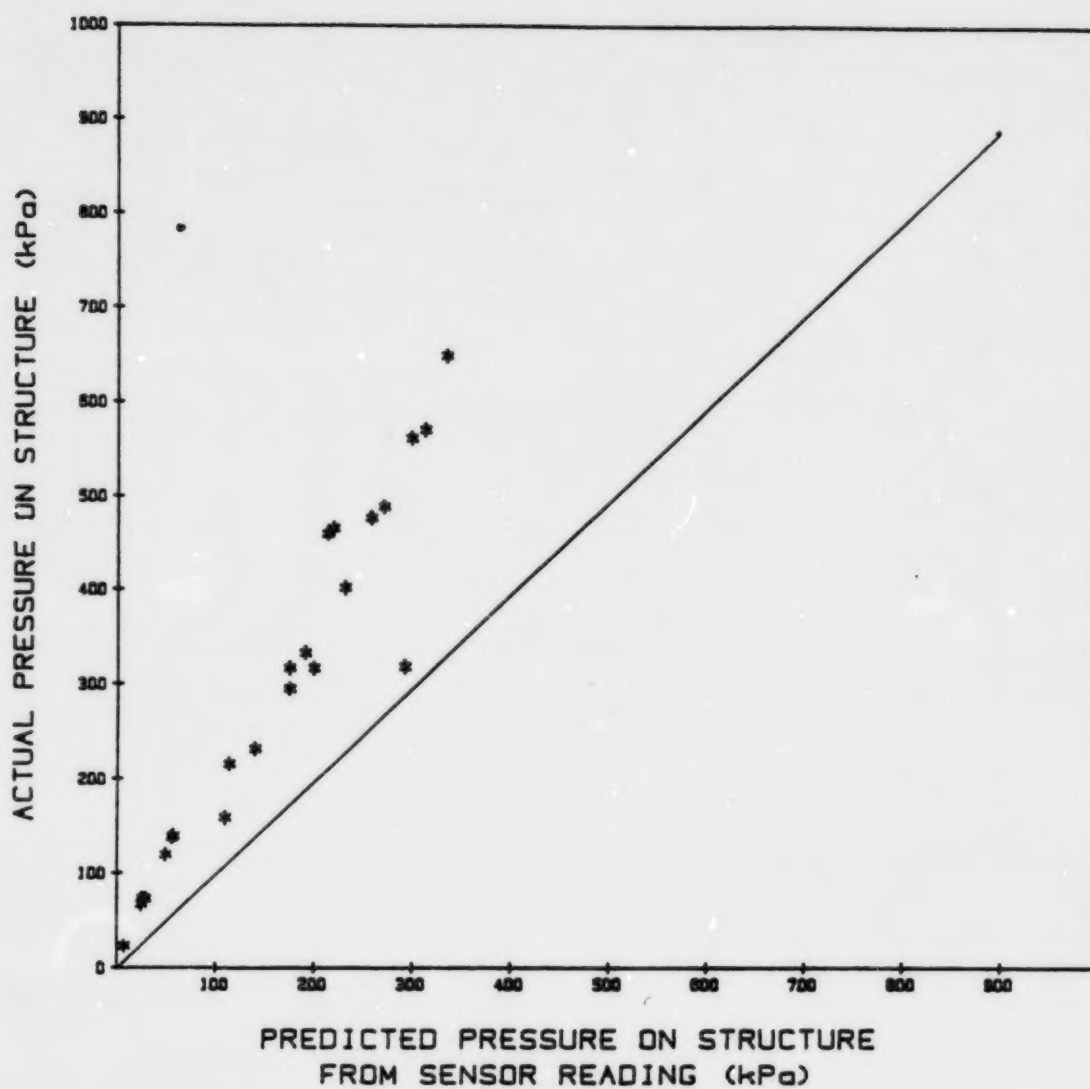


FIGURE 65 RESULTS OF UNSLOTTED TESTS
SENSOR: MEDOF PANEL

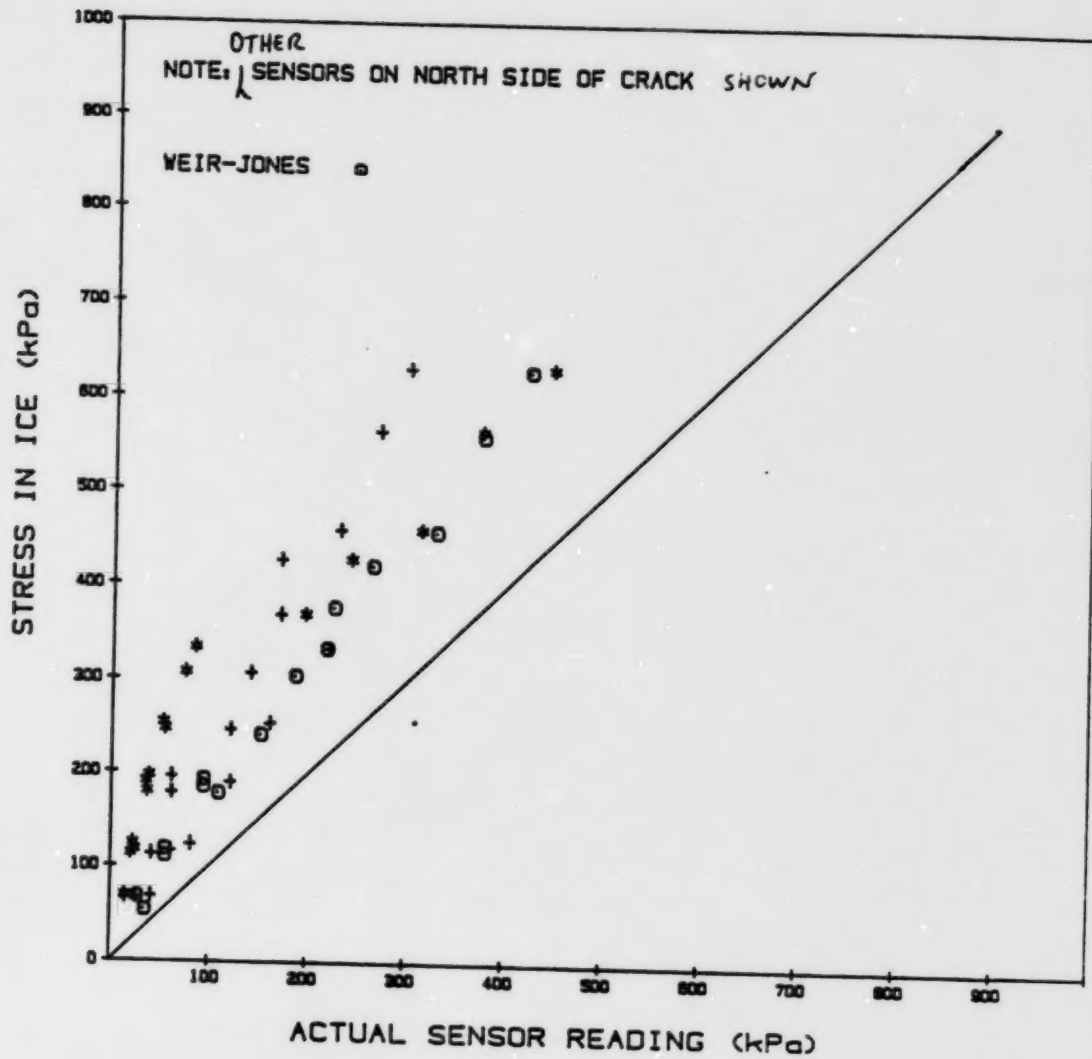


FIGURE 66 RESULTS OF SLOTTED TESTS
SENSORS: WEIR JONES.

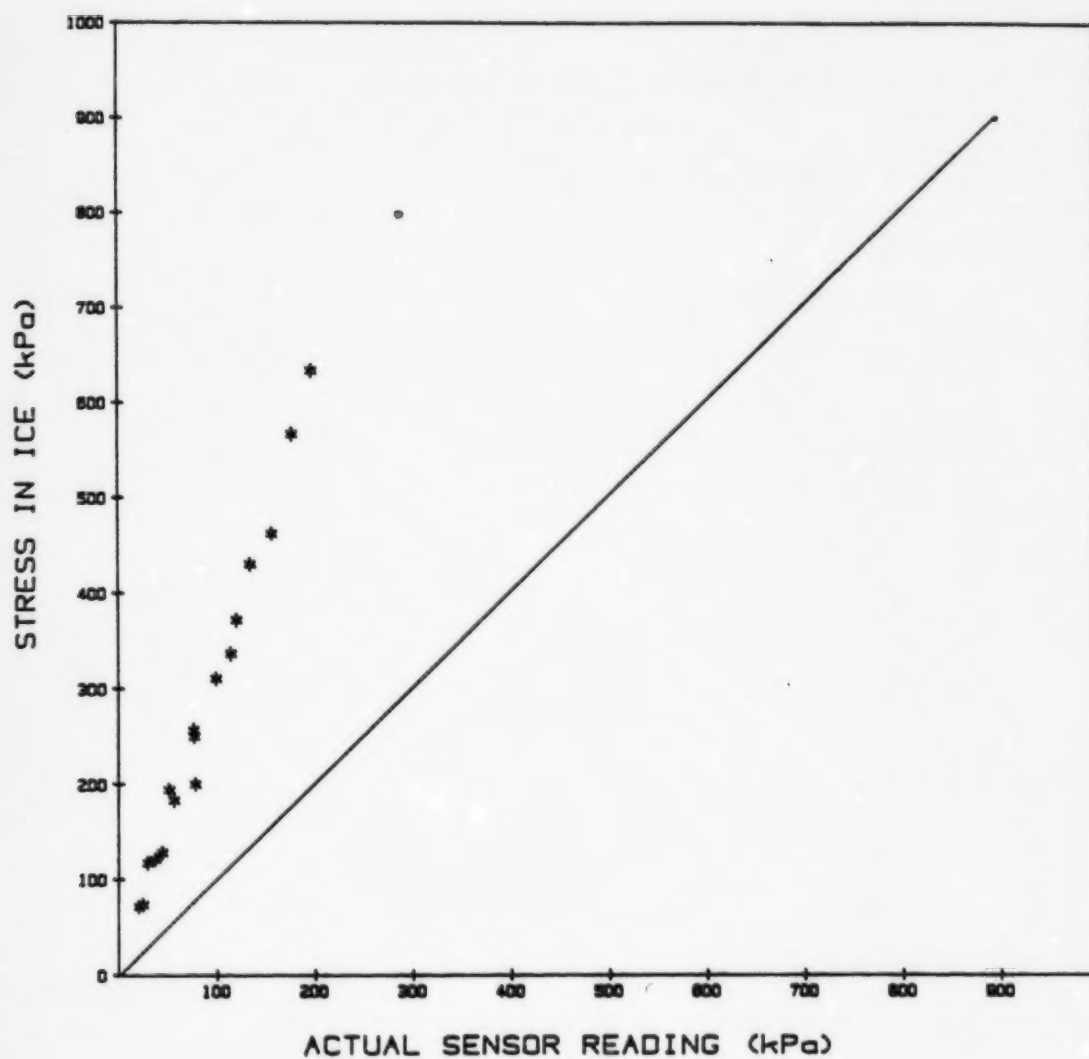


FIGURE 67 RESULTS OF SLOTTED TESTS
SENSOR: HEXPACK

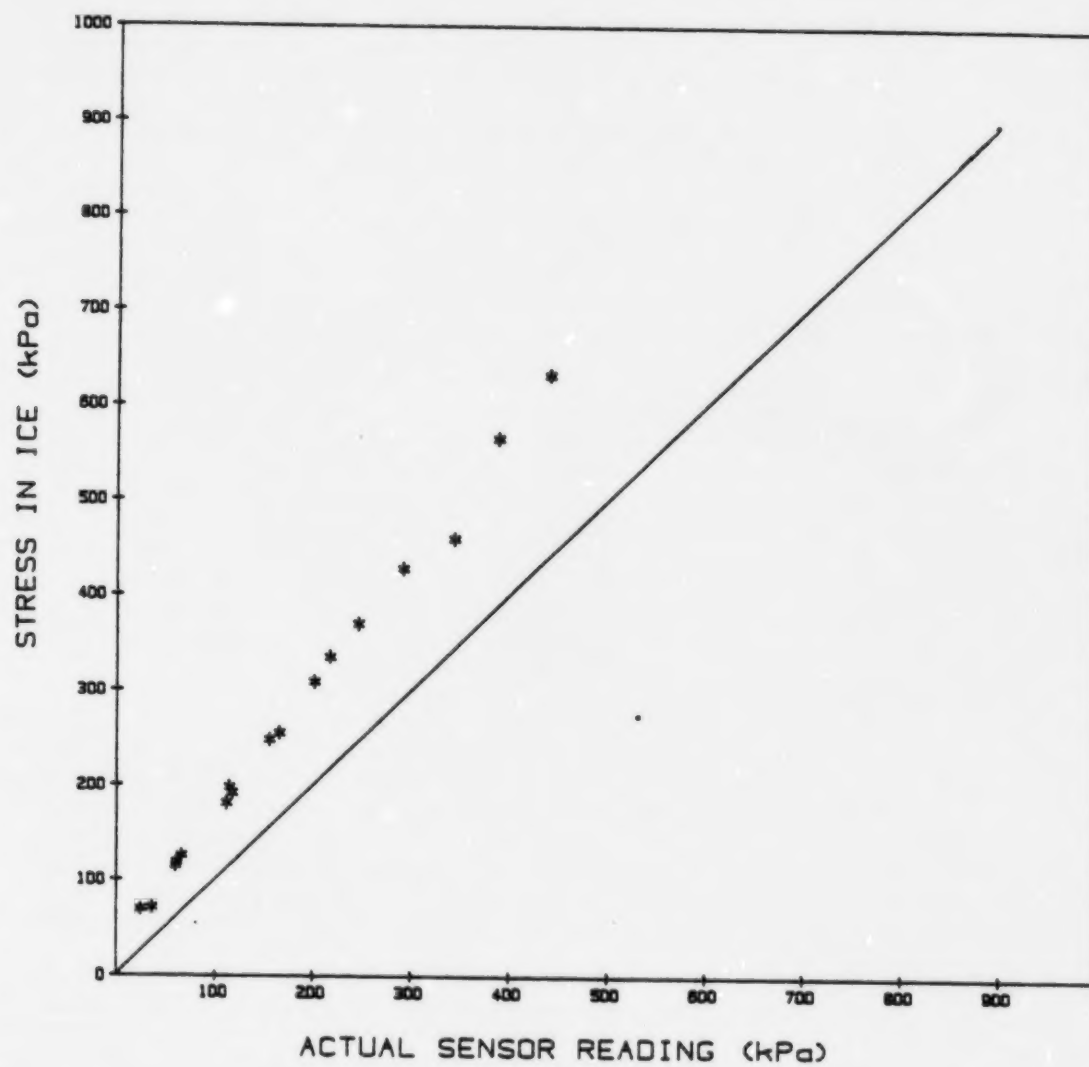


FIGURE 68 RESULTS OF SLOTTED TESTS
SENSOR: MEDOF

11.0 CONCLUSIONS

These two studies represent the most comprehensive evaluation of the ice pressure sensors yet performed. Each study complements the other. The Nanisivik project provided information on overall sensor performance in the arctic environment, the ice basin project provided a definitive evaluation of sensor accuracy under known load conditions.

Specifically the ice basin programme was quite successful. A total of 22 tests were performed of which 18 yielded reliable quantitative data. The maximum load achieved was 155 tons [1386 KN] corresponding to an ice stress of about 700 kPa. One test was performed during which the load was held constant for about three hours.

Some problems did occur which limited the scope and usefulness of the experiment. The weather was unusually warm for February so the ice was somewhat thinner than planned for. Also the warm weather affected the performance of some sensors in a way which would probably not have happened in the Arctic. The thinner ice combined with some tilting back of the structure caused some bending in the ice sheet which created problems of interpretation for some sensors. Finally the north reaction frame was less stiff than the others and it eventually failed, this led to unsymmetrical reaction forces on the structure which also created difficulties of interpretation in the sensor readings.

It should be recognized however that in the real world similar but sometimes different problems exist in going from a reading on an ice sensor to prediction of total load on a structure. In a sense this project gives a good indication of the reliability of prediction of total load from individual sensor readings. In this respect, the results from this project indicate that for most of the sensors the overall ability to calculate load on a structure from the sensor outputs is quite good.

In terms of the performance of different generic types of sensors this project indicates the following:

- . Sensors in the form of panels which average the ice stress through the full ice sheet thickness performed quite well. Any bending which might have been present did not create problems. Also, because of the unsymmetrical stress distribution, almost all the panels experienced some degree of biaxial stress [i.e. they were not necessarily facing the direction of maximum principal compressive stress]. Even so, their ability to measure the compressive stress normal to the reaction face did not seem to be adversely affected. This programme

appears to confirm that inclusion factors for thin wide panels are close to unity, and show no significant change during creep deformation of the ice. [Only the panel with a non-metallic interior exhibited a significant change of average stress during the creep test, and this was likely due to creep of the sensor itself.]

- . Sensors which sample stress at only one level through the ice sheet may introduce errors of interpretation because of the variation in ice stress through the thickness. In this experiment such a variation was partly due to induced bending, but even without bending, the stress distribution through an arctic ice sheet will not be uniform. On the other hand, if two levels of stress are measured then simple averaging appears to give reasonable agreement with the predicted stress.

- . Sensors which pass completely through the ice sheet [such as panels] may encourage any cracks which propagate to pass through their location.

Some criticism might be directed at the use of an elastic stress distribution to translate sensor readings into an equivalent ice pressure on the structure. Ideally a stress analysis incorporating time-dependent deformation [or pseudo-plasticity] would be better - but more difficult. We have not attempted to perform a more complex analysis because the use of the elastic solution to convert sensor readings to ice pressures on the structure seems to work quite well. Furthermore a review of the recent work by Wang and Ralston [1983] indicates that in terms of radial compressive stress there is little difference between the elastic and plastic solutions.

Overall, the ice basin programme indicated that for those sensors which were operational, the average percentage difference between the actual ice loads on the structure and those based on sensor readings was less than 30%.

At the Nanisivik Dock the ice sensors were subject to complex stress states under typical arctic conditions. The main points of conclusion from the Nanisivik programme are as follows:

- . All sensors showed a strong correlation of ice pressure peaks with tidal action.

- . Maximum compressive stress in the ice occurred close to low tide.

- . The ice around the dock appeared to be in a confined stress state, as those sensors measuring stress parallel to the shore showed relatively high

compressive ice pressures in association with the compressive ice pressures against the dock.

- . Direct comparison of sensor readings, and an evaluation of sensor accuracy is not possible from this programme because of the complex stress state in the ice, and the presence of cracks which presumably created stress discontinuities over short distances.

- . A time-averaged value of compressive ice pressure of about 100 kPa would explain the slow movement of the level ice away from the dock over a 3 month period.

- . Such a value is not incompatible with the general level of ice pressure indicated by the sensors.

- . However some sensors did indicate peak pressures [averaged through the ice thickness] up to 1000 kPa.

- . However these high values were from sensors and/or data acquisition systems which were faulty. Hence the occurrence of such high stress levels is open to question.

- . Undoubtably, however, stresses greater than 500 kPa did occur locally through the ice thickness as a result of combining tidal flexural stresses and direct compressive stresses.

- . The strain meters functioned satisfactorily and recorded surface strains during the test period. These also showed a strong correlation with tidal action. However due to the extremely complex stress state, and addition of short term flexural strains to longer-term compressive strains it is considered virtually impossible to convert the strains to stresses.

- . Three of the four data acquisition systems exhibited problems during the test period. In some cases due to lack of preparation time and pre-checking before shipping to the field.

The strongest recommendation that can be made from the Nanisivik experience is that all data acquisition systems be assembled with their sensors in the South and thoroughly checked before shipping to the field. These checks should involve not just hardware, but any software used in microprocessor units.

. The ice conditions which prevailed at the Nanisivik Dock during the 1983/84 winter were very similar to those reported by previous investigators [notably, Frederking]. The ice conditions appear to be dominated by tidal motion of the landfast ice in the Sound.

. Installation of both panel-type sensors and cylindrical sensors can be accomplished quite easily using chain saws and augers. Removal is not so easy with chain saws, especially large panels for which lifting gear is required. Portable steamer systems should be developed for sensor removal.

. In-situ calibrations conducted at Nanisivik were generally not satisfactory. In hindsight more effort should have been put into obtaining proper zero readings at the end of the monitoring period.

12.0 ACKNOWLEDGEMENTS

Both these projects were funded either in total or in part by the Government of Canada. The involvement and support given by Dr. M. Cheung of Public Works and Dr. R. Frederking of the National Research Council is gratefully acknowledged.

The Nanisivik project could not have been carried out without the logistical support of Nanisivik Mines Ltd., Mr. D. Johnson and Mr. C. Thom and others at the mine gave specific assistance and this also is gratefully acknowledged.

Esso Resources Canada Ltd. deserves special mention for allowing their ice test basin to be rented for the Calgary project. The helpful attitude of their staff is also gratefully acknowledged.



13.0 REFERENCES

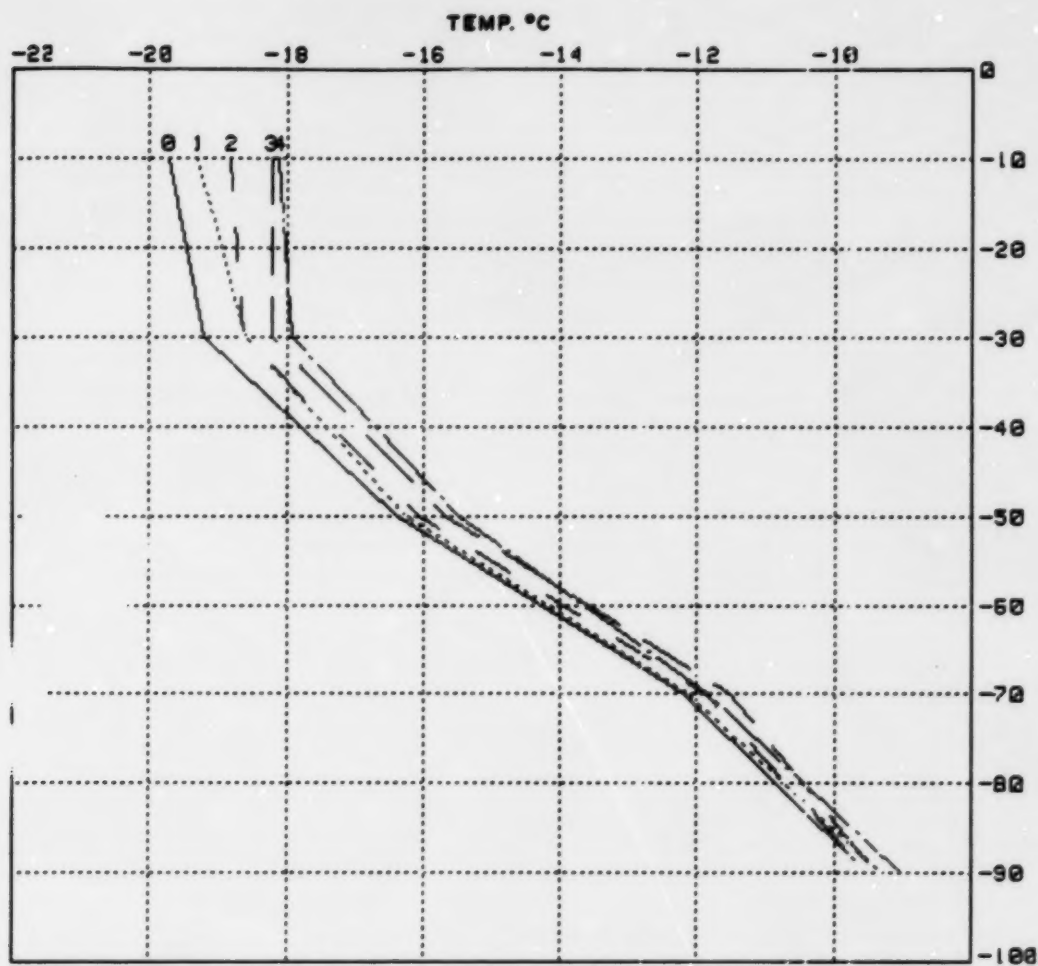
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A P P E N D I X A

NANISIVIK TEMPERATURE DATA

NANISIVIC TEMPERATURE PROFILE

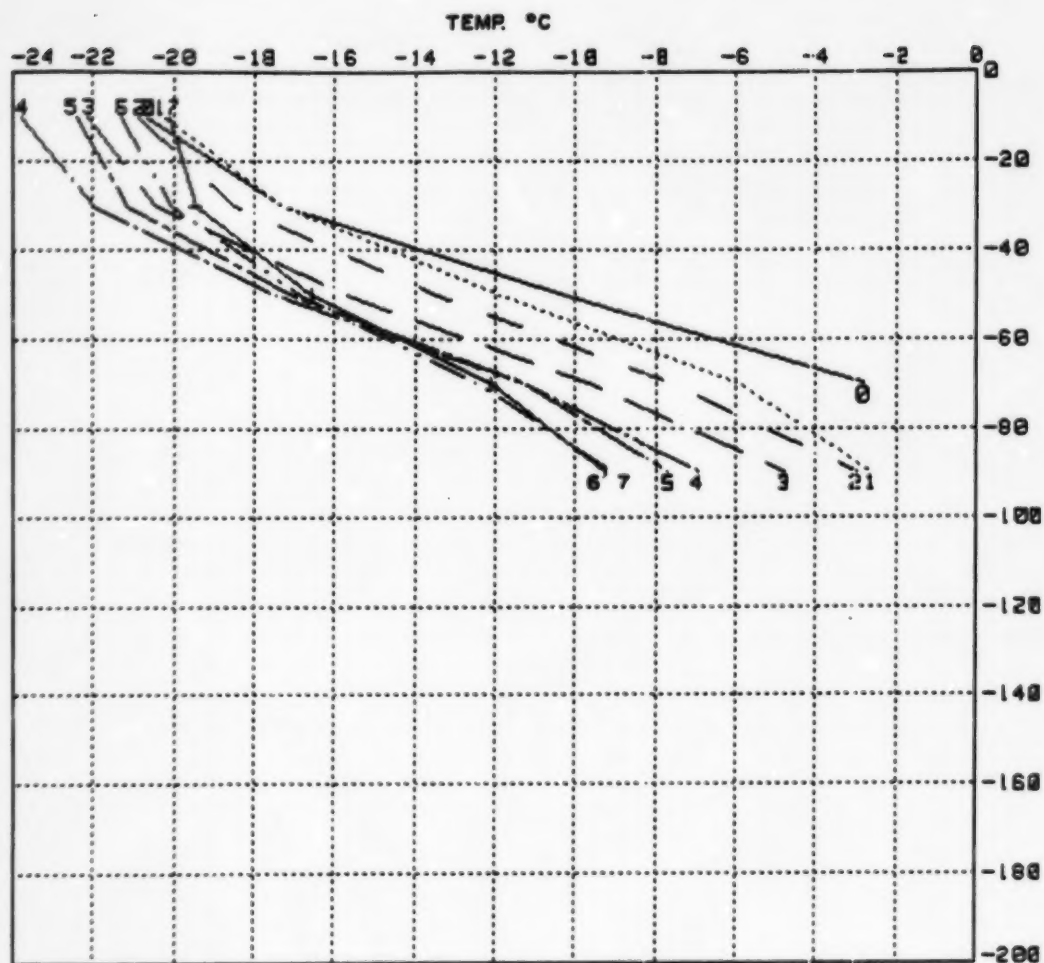


0
1
2
3
4

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Date=13/3
Date=14/3
Date=14/3
Date=15/3

TIME=8:20
TIME=20:50
TIME=9:20
TIME=21:50
TIME=10:20

NANISIVIC TEMPERATURE PROFILES

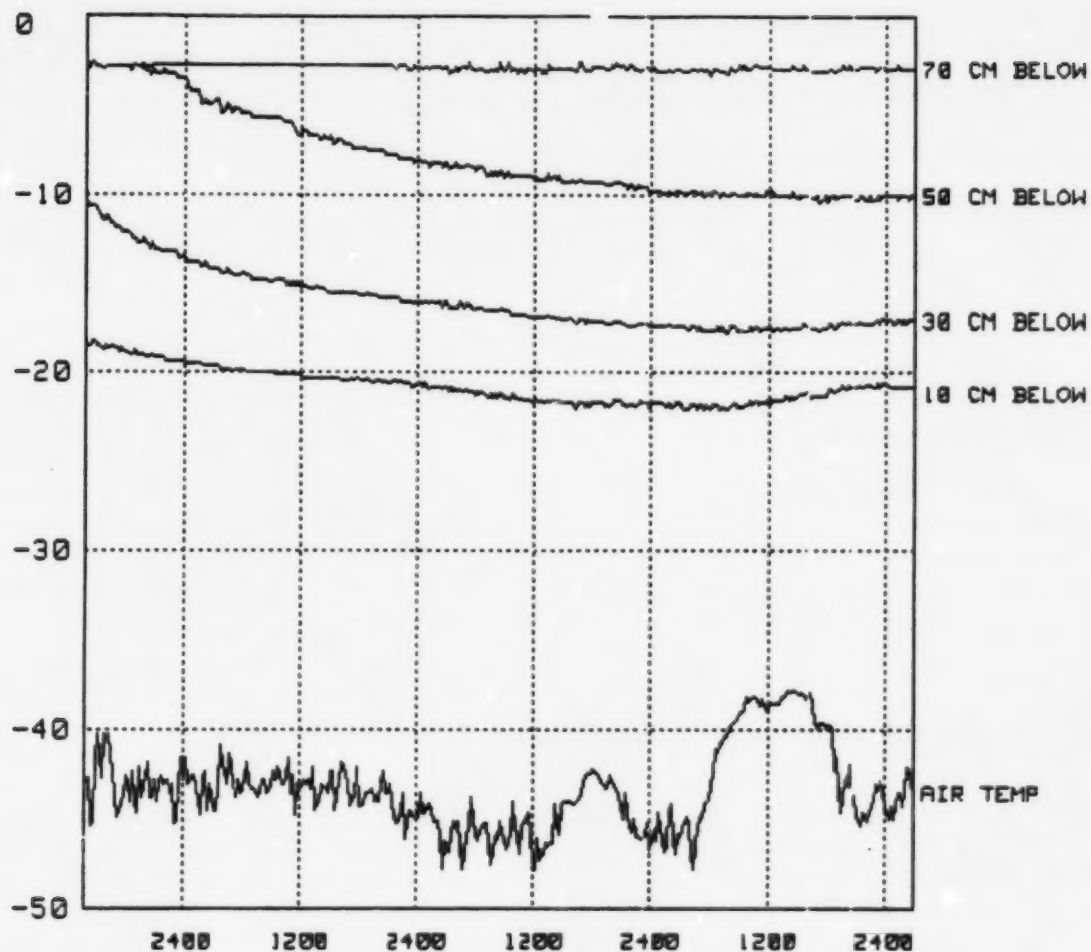


0
1
2
3
4
5
6
7

Date=5/1
Date=13/1
Date=20/1
Date=27/1
Date=3/2
Date=10/2
Date=24/2
Date=9/3

TIME=22:7
TIME=11:52
TIME=12:7
TIME=12:7
TIME=12:7
TIME=12:20
TIME=12:20
TIME=12:5

NANISIVIC TEMPERATURE DATA

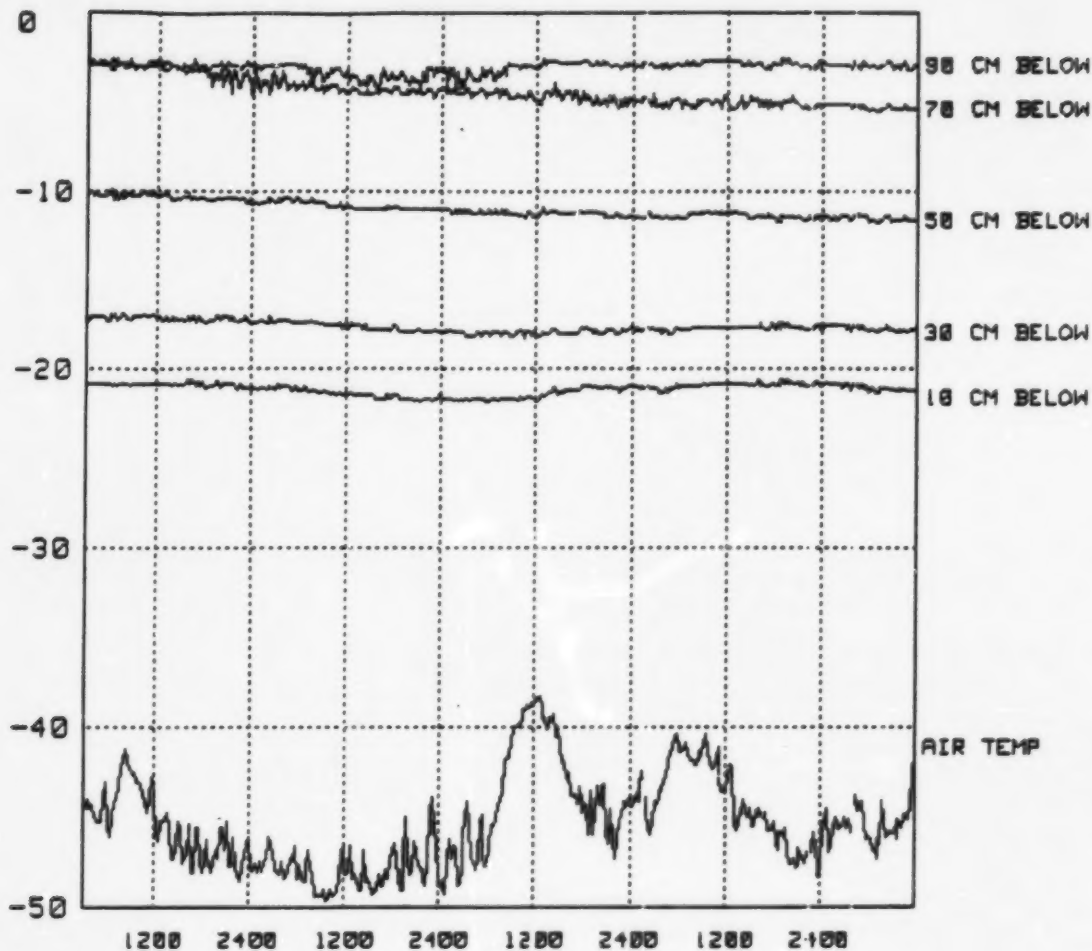


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NANO CHANNELS

22
 23
 24
 25
 31

NANISIVIC TEMPERATURE DATA

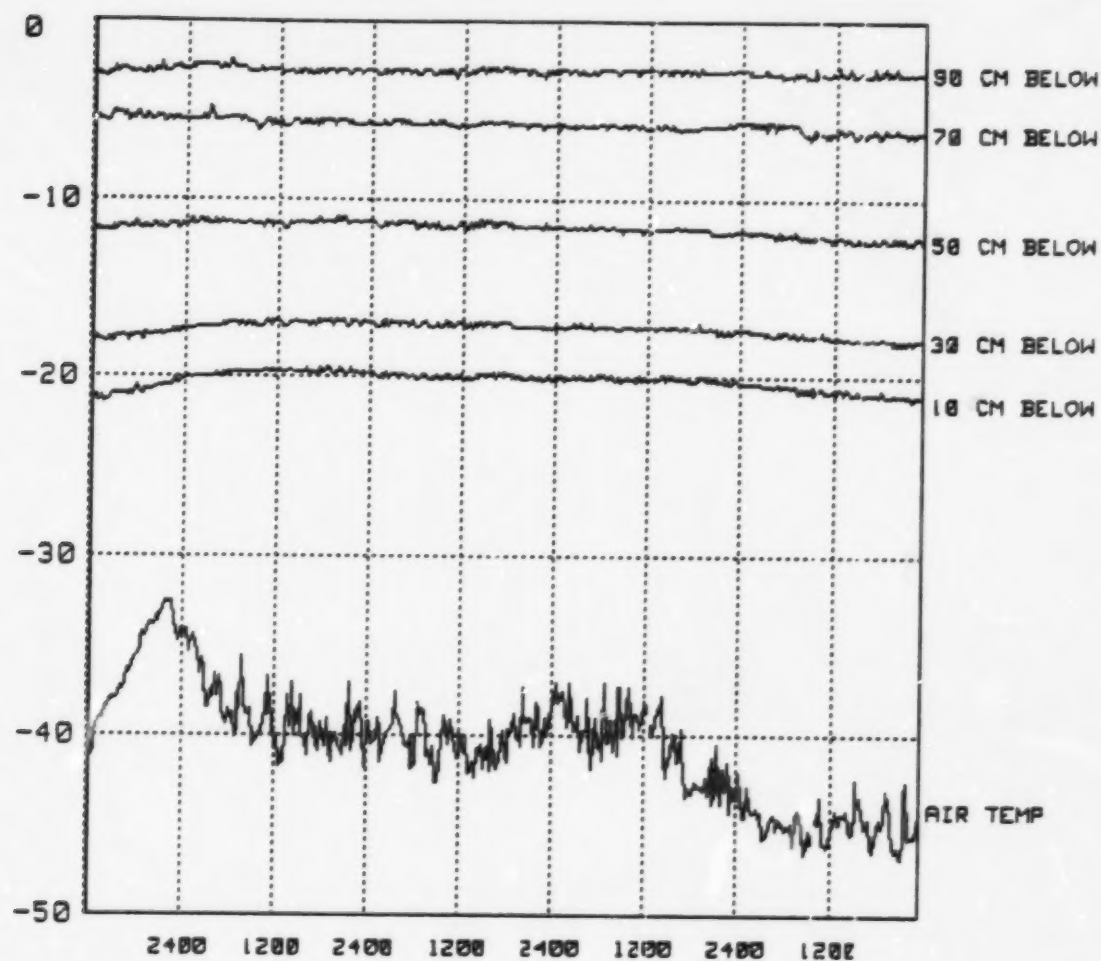


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NANI CHANNELS

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 23
 24
 25
 26
 31

NANISIVIC TEMPERATURE DATA

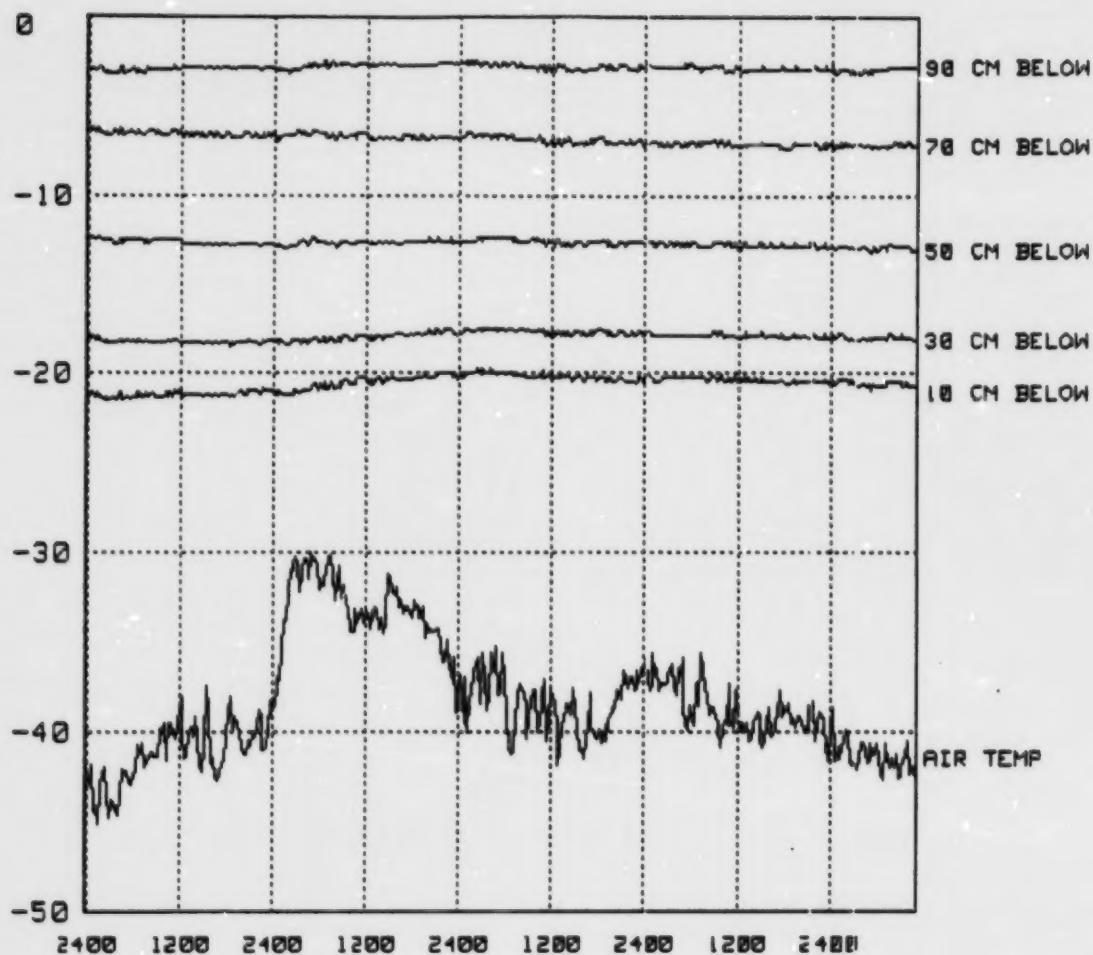


START DATE (DAY/MONTH) =10/1
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 ENDING TIME =23:22

NAN2 CHANNELS

22
 23
 24
 25
 26
 31

NANISIVIC TEMPERATURE DATA

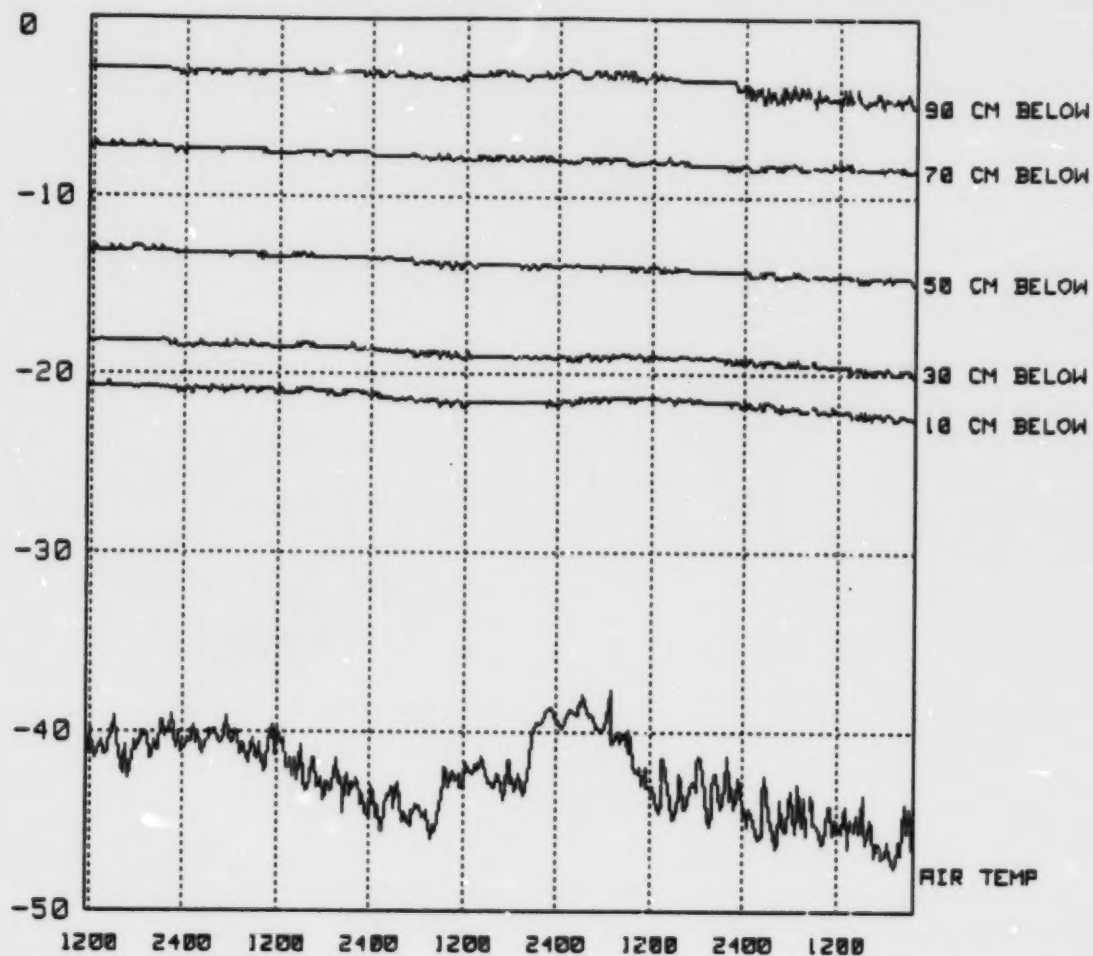


START DATE (DAY/MONTH) =14/1
 START TIME =23:37
 ENDING DATE (DAY/MONTH)=19/1
 ENDING TIME =11:7

NAN3 CHANNELS

22
 23
 24
 25
 26
 31

NANISIVIC TEMPERATURE DATA

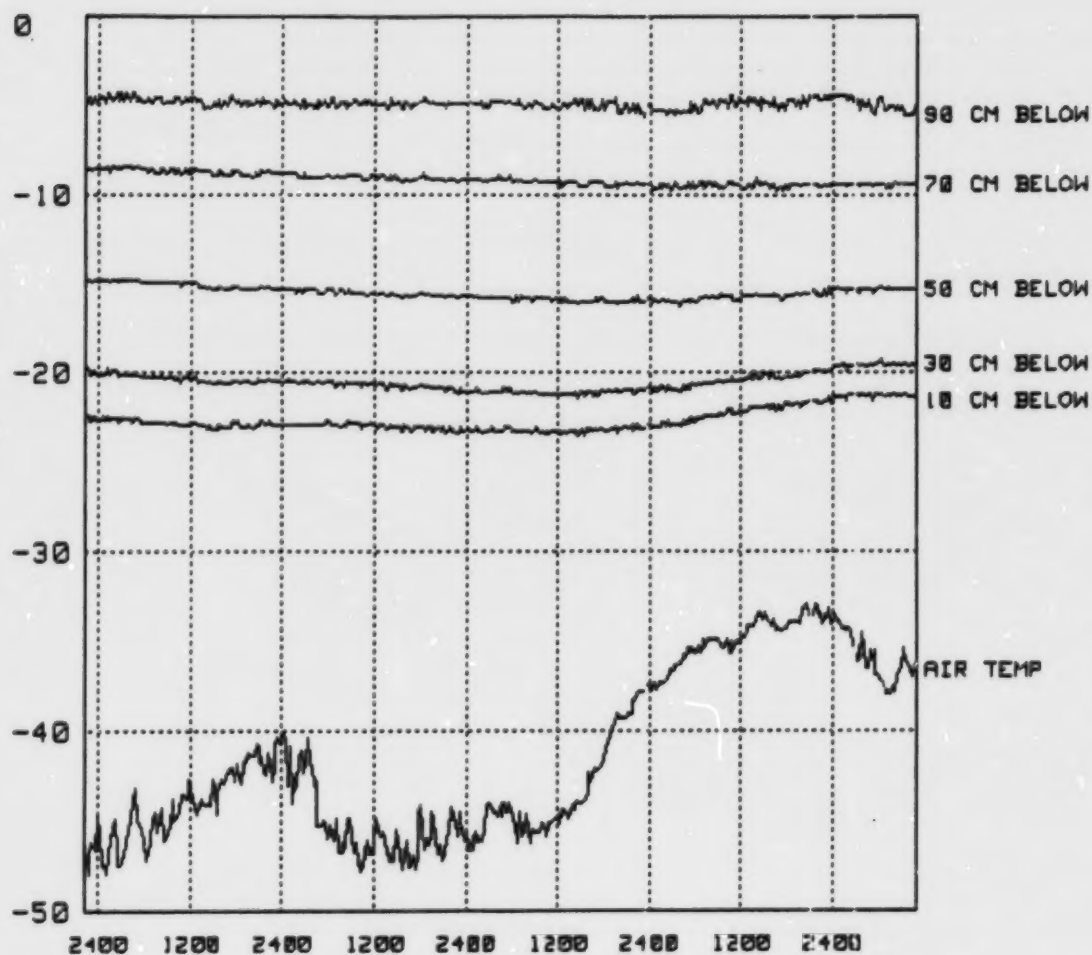


START DATE (DAY/MONTH) =19/1
START TIME =11:22
ENDING DATE (DAY/MONTH)=23/1
ENDING TIME =21:52

NAN4 CHANNELS

22
23
24
25
26
31

NANISIVIC TEMPERATURE DATA

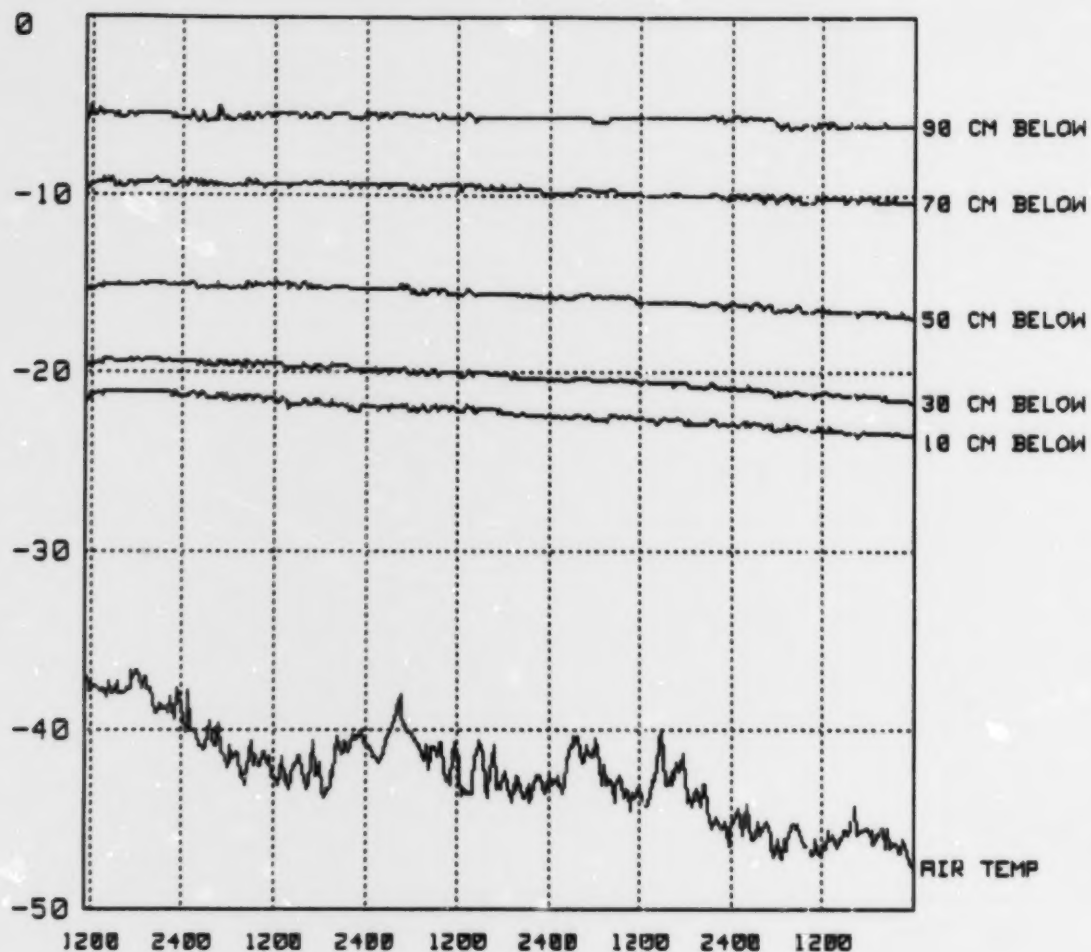


START DATE (DAY/MONTH) =23/1
 START TIME =22:7
 ENDING DATE (DAY/MONTH)=28/1
 ENDING TIME =10:52

NAN5 CHANNELS

22
 23
 24
 25
 26
 31

NANISIVIC TEMPERATURE DATA

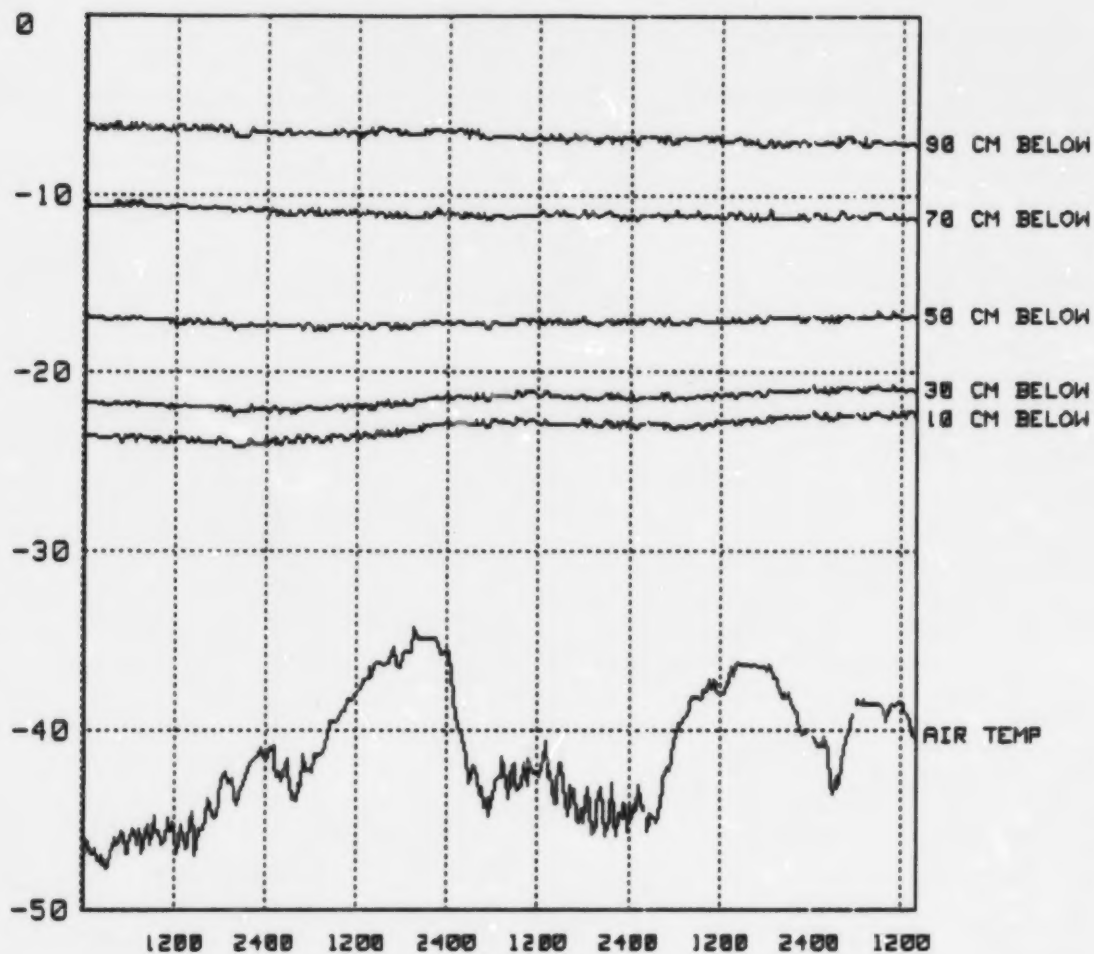


START DATE (DAY/MONTH) =28/1
 START TIME =11:7
 ENDING DATE (DAY/MONTH)=1/2
 ENDING TIME =23:52

NAN6 CHANNELS

22
 23
 24
 25
 26
 31

NANISIVIC TEMPERATURE DATA

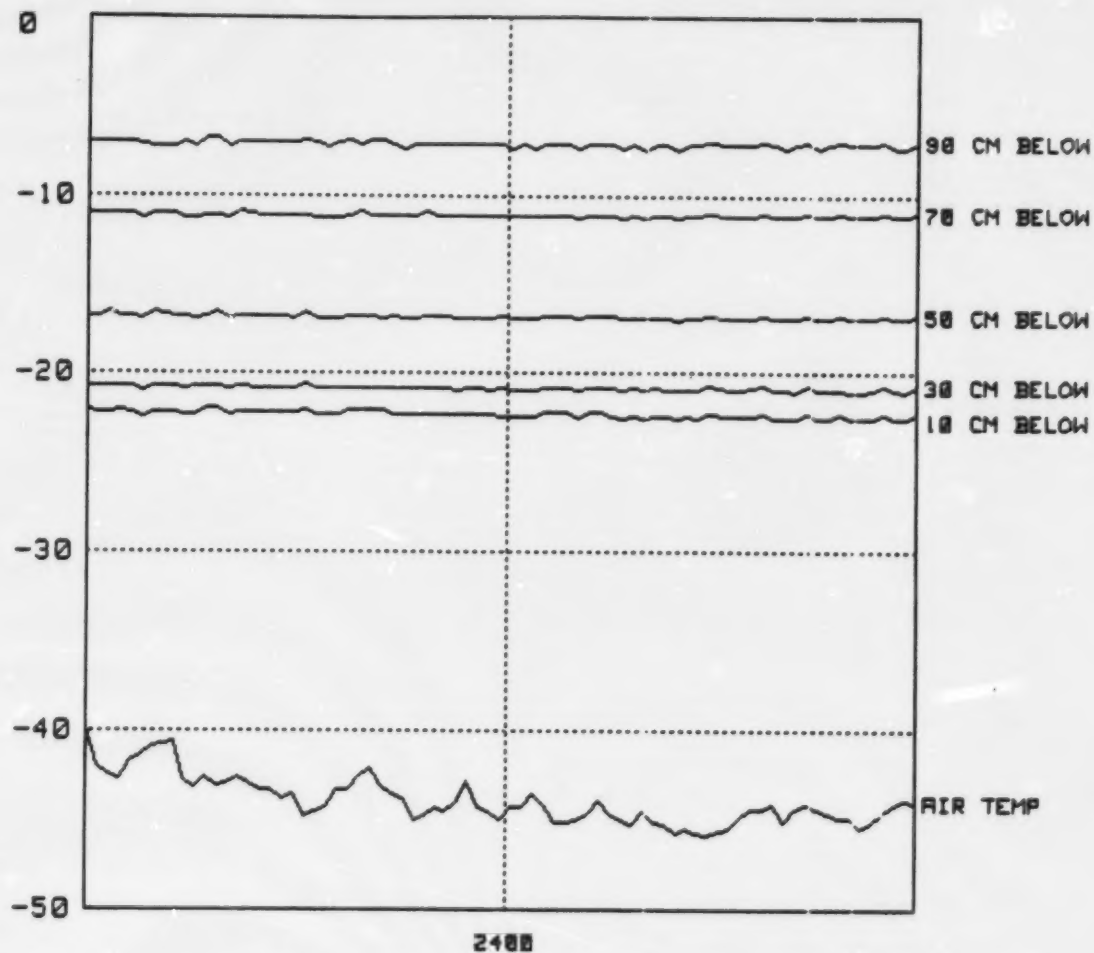


START DATE (DAY/MONTH) =2/2
 START TIME =0:7
 ENDING DATE (DAY/MONTH)=6/2
 ENDING TIME =13:52

NAN7 CHANNELS

22
 23
 24
 25
 26
 31

NANISIVIC TEMPERATURE DATA

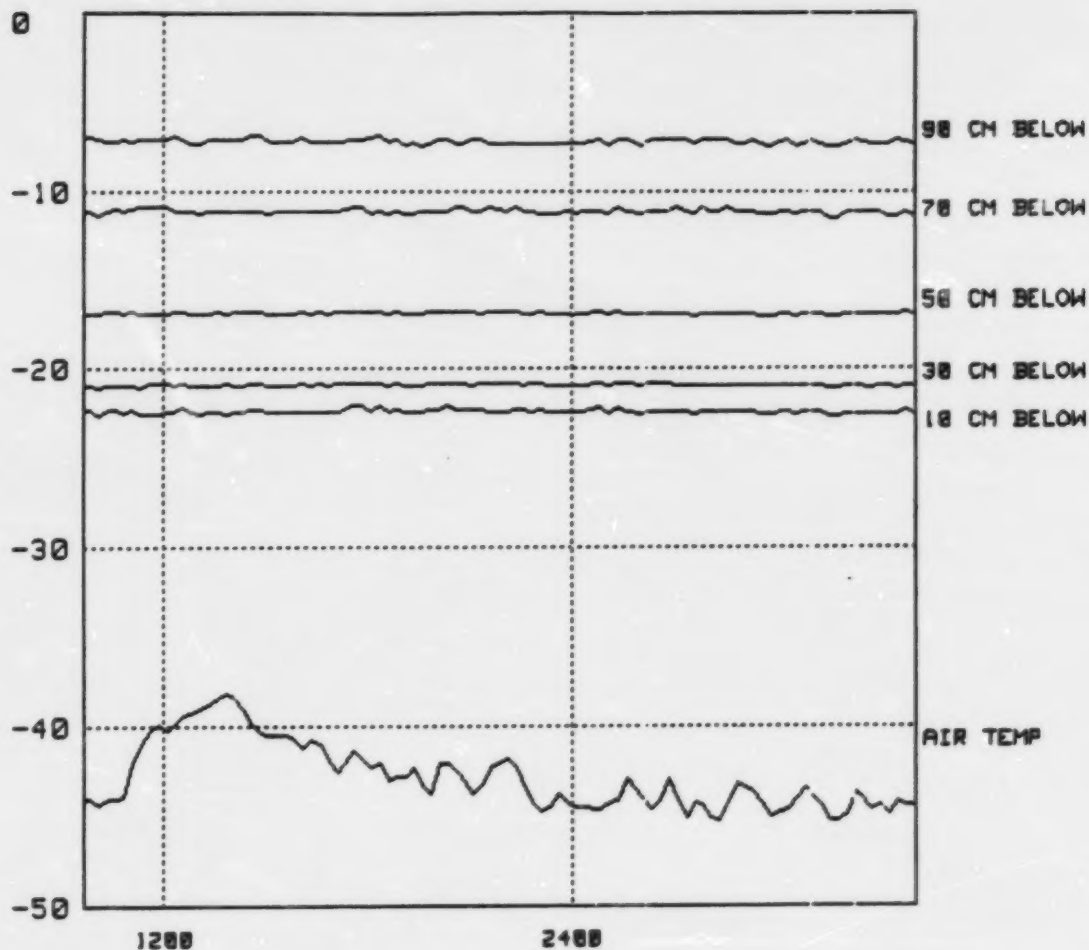


START DATE (DAY/MONTH) =6/2
START TIME =14:22
ENDING DATE (DAY/MONTH)=7/2
ENDING TIME =9:22

NAN8 CHANNELS

22
23
24
25
26
31

NANISIVIC TEMPERATURE DATA

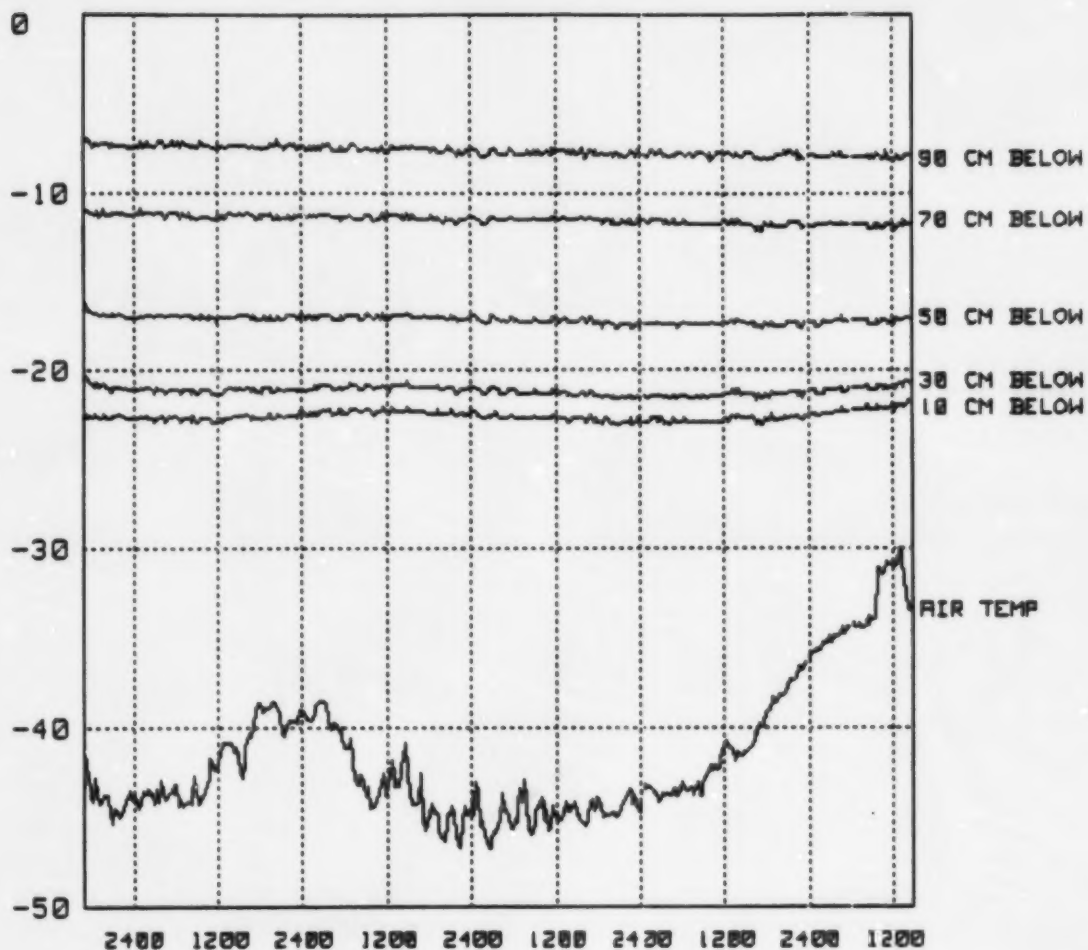


START DATE (DAY/MONTH) =7/2
 START TIME =9:52
 ENDING DATE (DAY/MONTH)=8/2
 ENDING TIME =10:7

NAN20a CHANNELS

22
 23
 24
 25
 26
 31

NANISIVIC TEMPERATURE DATA

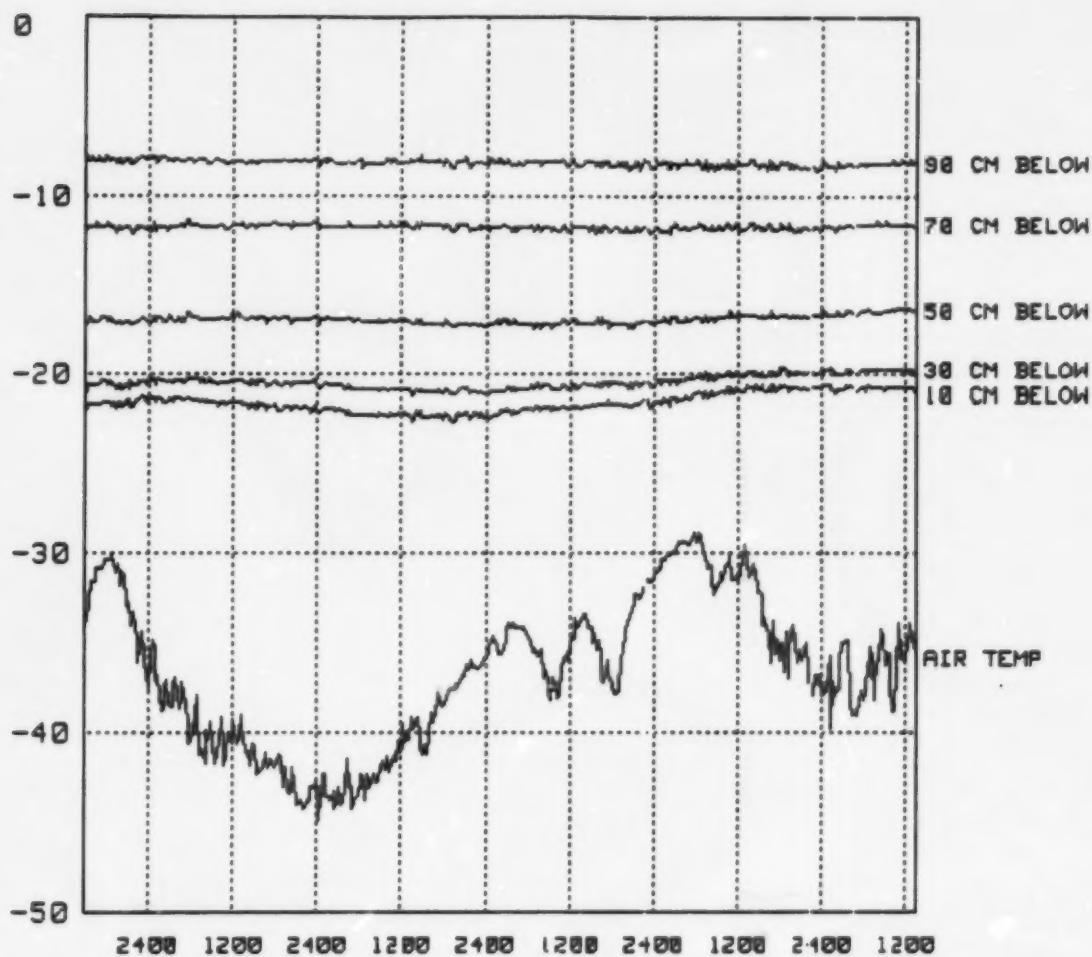


START DATE (DAY/MONTH) = 9/2
 START TIME = 16:50
 ENDING DATE (DAY/MONTH) = 13/2
 ENDING TIME = 14:35

NAN20b CHANNELS

22
 23
 24
 25
 26
 31

NANISIVIC TEMPERATURE DATA

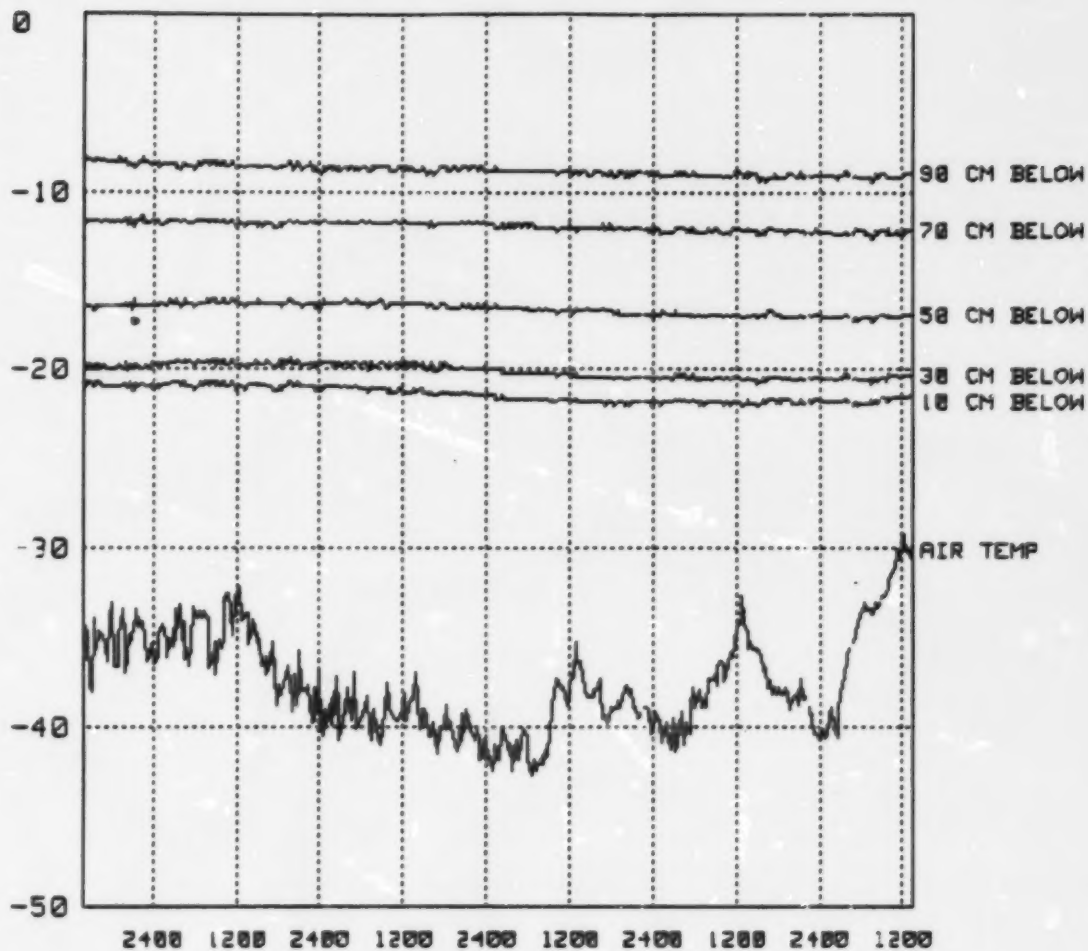


START DATE (DAY/MONTH) =13/2
 START TIME =14:50
 ENDING DATE (DAY/MONTH)=18/2
 ENDING TIME =13:20

NAN21 CHANNELS

22
 23
 24
 25
 26
 31

NANISIVIC TEMPERATURE DATA

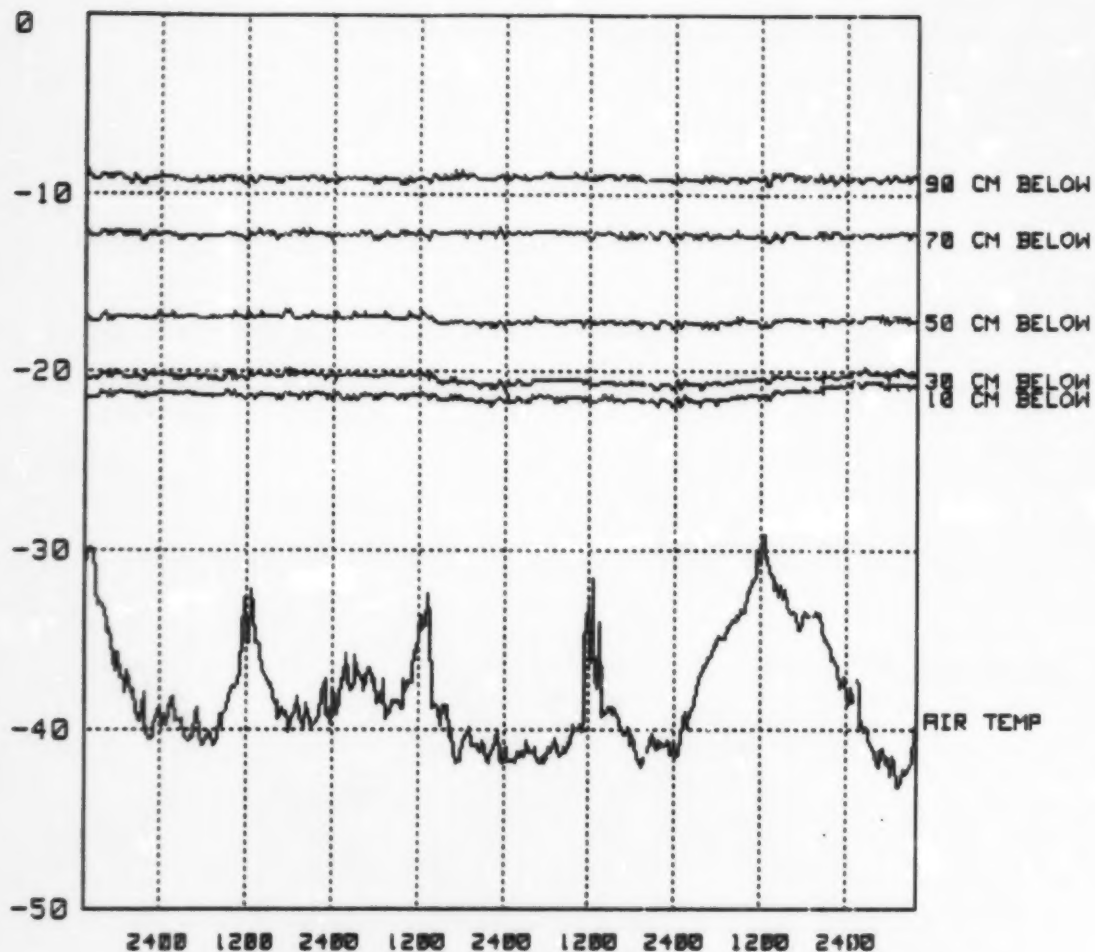


START DATE (DAY/MONTH) =18/2
 START TIME =13:50
 ENDING DATE (DAY/MONTH)=23/2
 ENDING TIME =13:20

NAN22 CHANNELS

22
 23
 24
 25
 26
 31

NANISIVIC TEMPERATURE DATA

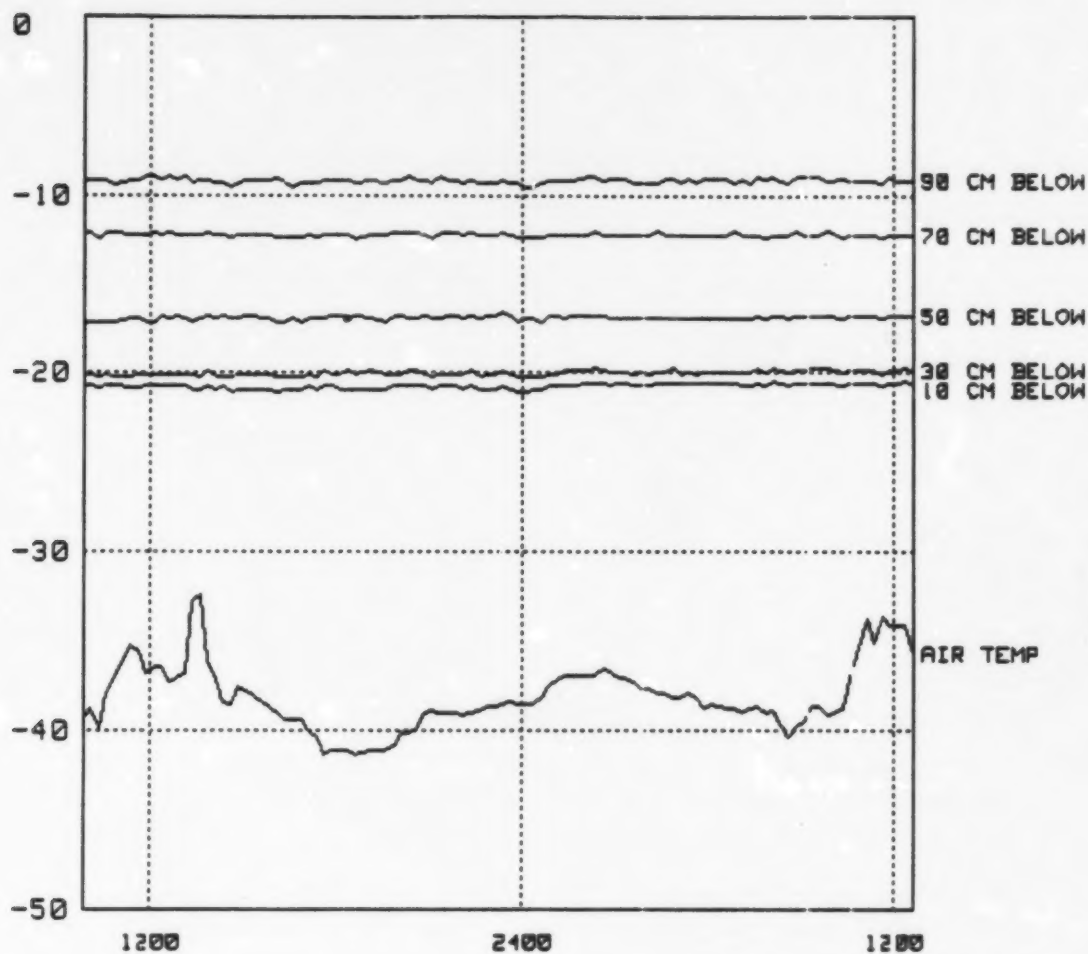


START DATE (DAY/MONTH) =23/2
 START TIME =13:35
 ENDING DATE (DAY/MONTH)=28/2
 ENDING TIME =9:35

NAN23 CHANNELS

22
 23
 24
 25
 26
 31

NANISIVIC TEMPERATURE DATA

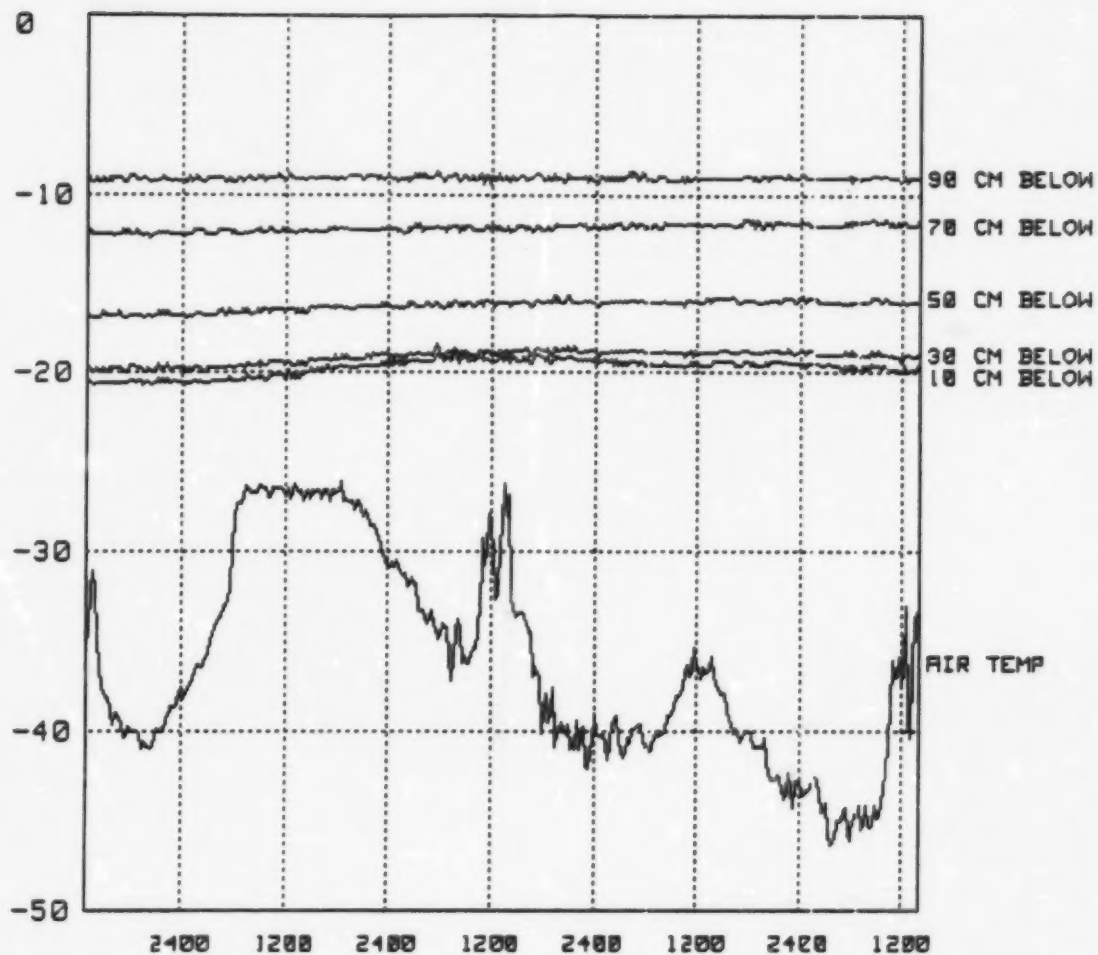


START DATE (DAY/MONTH) =28/2
START TIME =9:50
ENDING DATE (DAY/MONTH)=29/2
ENDING TIME =12:35

NAN24 CHANNELS

22
23
24
25
26
31

NANISIVIC TEMPERATURE DATA

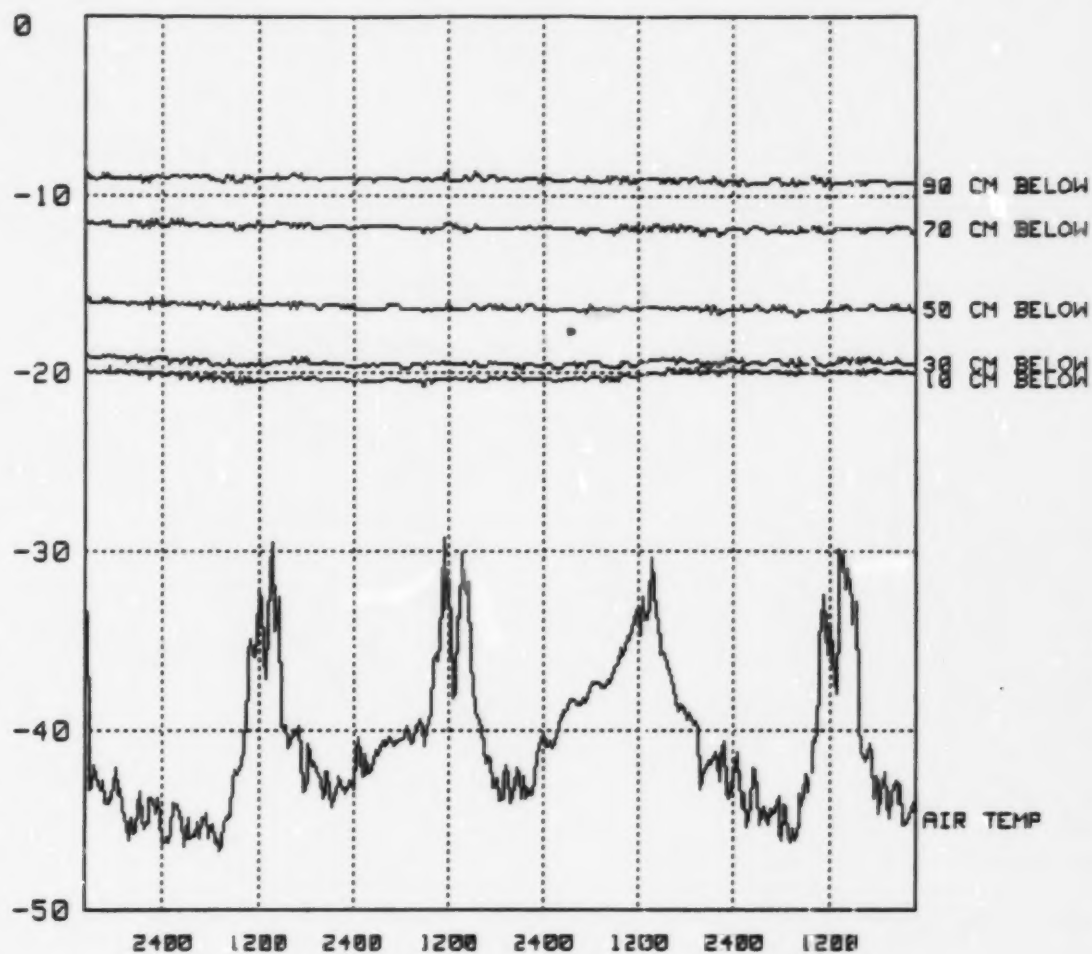


START DATE (DAY/MONTH) =29/2
 START TIME =12:50
 ENDING DATE (DAY/MONTH)=4/3
 ENDING TIME =13:50

RATE CHANNELS

22
 23
 24
 25
 26
 31

NANISIVIC TEMPERATURE DATA

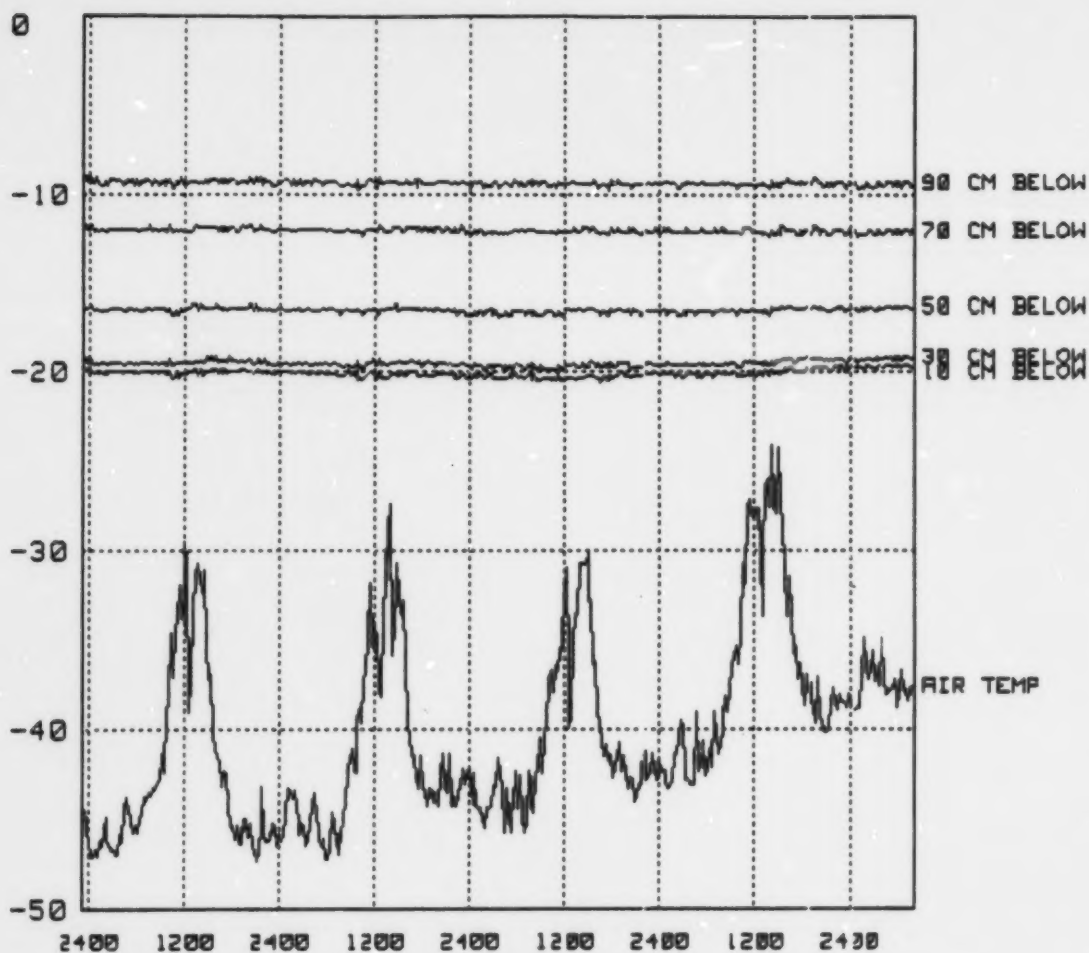


START DATE (DAY/MONTH) =4/3
 START TIME =14:5
 ENDING DATE (DAY/MONTH)=8/3
 ENDING TIME =22:50

RAT1 CHANNELS

22
 23
 24
 25
 26
 31

NANTISIVIC TEMPERATURE DATA

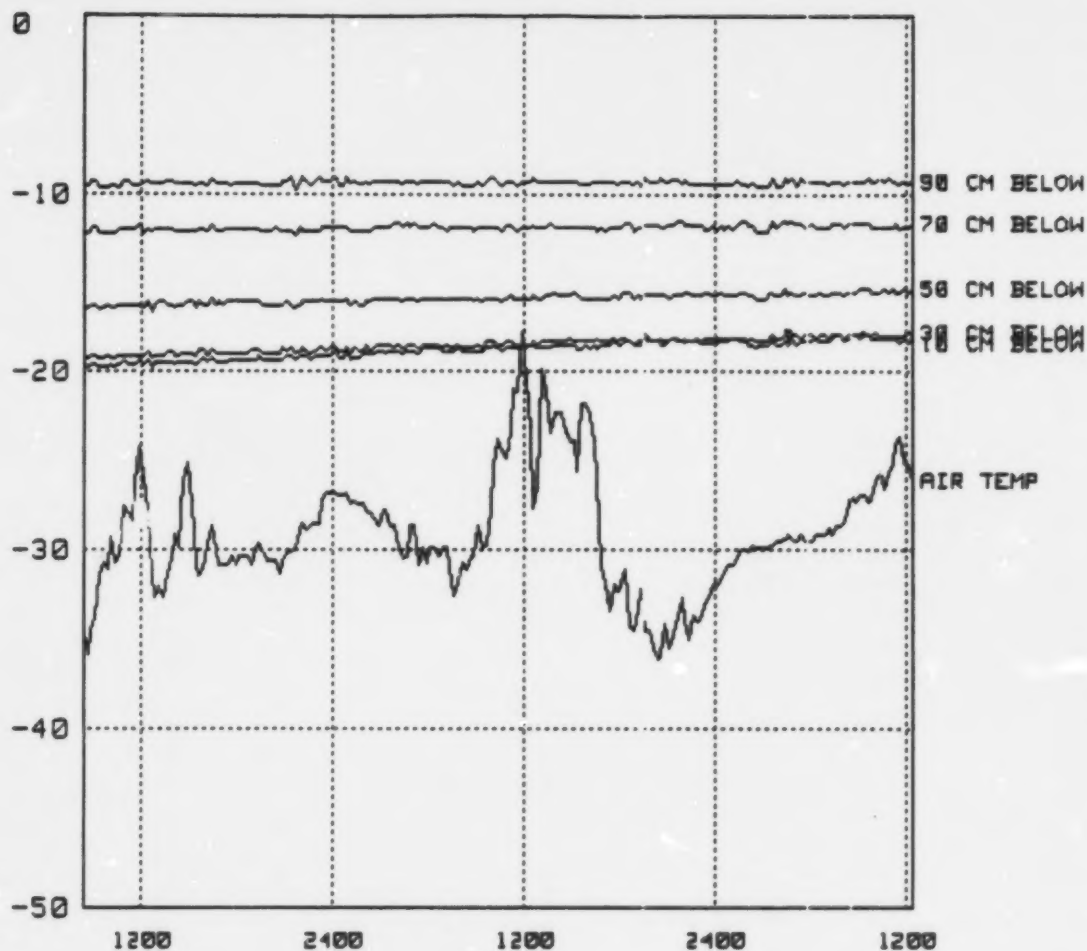


START DATE (DAY/MONTH) =8/3
 START TIME =23:5
 ENDING DATE (DAY/MONTH)=13/3
 ENDING TIME =8:5

RAT2 CHANNELS

22
 23
 24
 25
 26
 31

NANISIVIC TEMPERATURE DATA



START DATE (DAY/MONTH) =13/3
START TIME =8:20
ENDING DATE (DAY/MONTH) =15/3
ENDING TIME =12:20

RAT3 CHANNELS

22
23
24
25
26
31

On the following table the * indicates that no temperatures were obtained on that day (ie. the airport at Nanisivik was closed).

Maximum and Minimum Temperatures for Nanisivik:
January 1 to March 31, 1984.

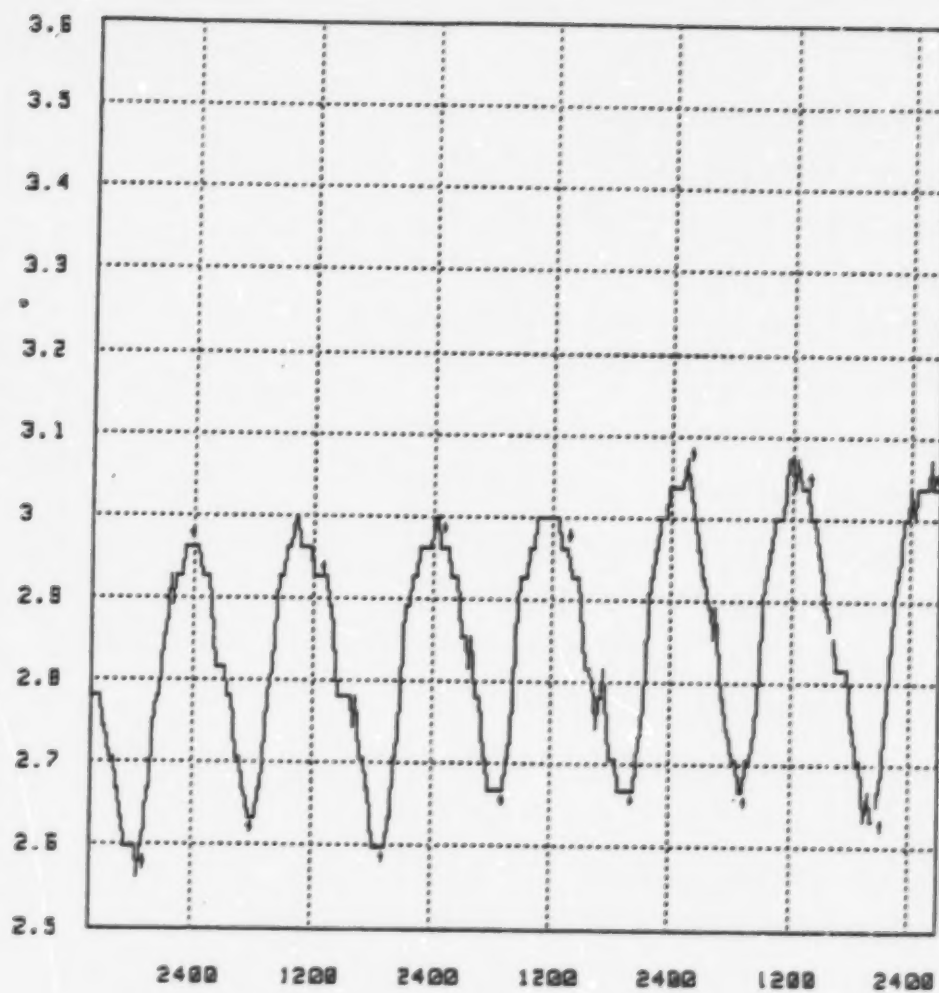
Day	January		February		March	
	max.	min.	max.	min.	max.	min.
1	*	*	-38	-39	-31	-32
2	-27	-30	-36	-38	-32	-34
3	-30	-32	-39	-40	-39	-40
4	-32	-35	-37	-40	-37	-40
5	-34	-36	*	*	*	*
6	-37	-40	-37	-39	-37	-39
7	-36	-38	-36	-38	-36	-38
8	*	*	-34	-37	-34	-40
9	-40	-42	-34	-37	-38	-41
10	-32	-36	-34	-37	-38	-41
11	-28	-31	-28	-32	*	*
12	-30	-32	*	*	-23	-28
13	-31	-34	-35	-35	-22	-25
14	-32	-34	-33	-35	-25	-26
15	*	*	-28	-30	-30	-33
16	-31	-38	-29	-31	-36	-37
17	-31	-36	-26	-29	-35	-36
18	-29	-32	-25	-27	*	*
19	-30	-32	*	*	-32	-34
20	-30	-33	-29	-31	-30	-33
21	-29	-31	-30	-33	-31	-34
22	*	*	-32	-32	-27	-29
23	-35	-40	-29	-31	-23	-25
24	-40	-43	-29	-31	-21	-23
25	-37	-39	-27	-29	*	*
26	-26	-32	*	*	-16	-17
27	-26	-29	-29	-32	-15	-17
28	-27	-29	-34	-37	-17	-18
29	*	*	-29	-32	-16	-18
30	-32	-34	xxx	xxx	-15	-17
31	-35	-40	xxx	xxx	-19	-22

A P P E N D I X B

NANISIVIK TIDE DATA

NANISIVIC TIDE DATA

DEPTH (METERS) VS TIME

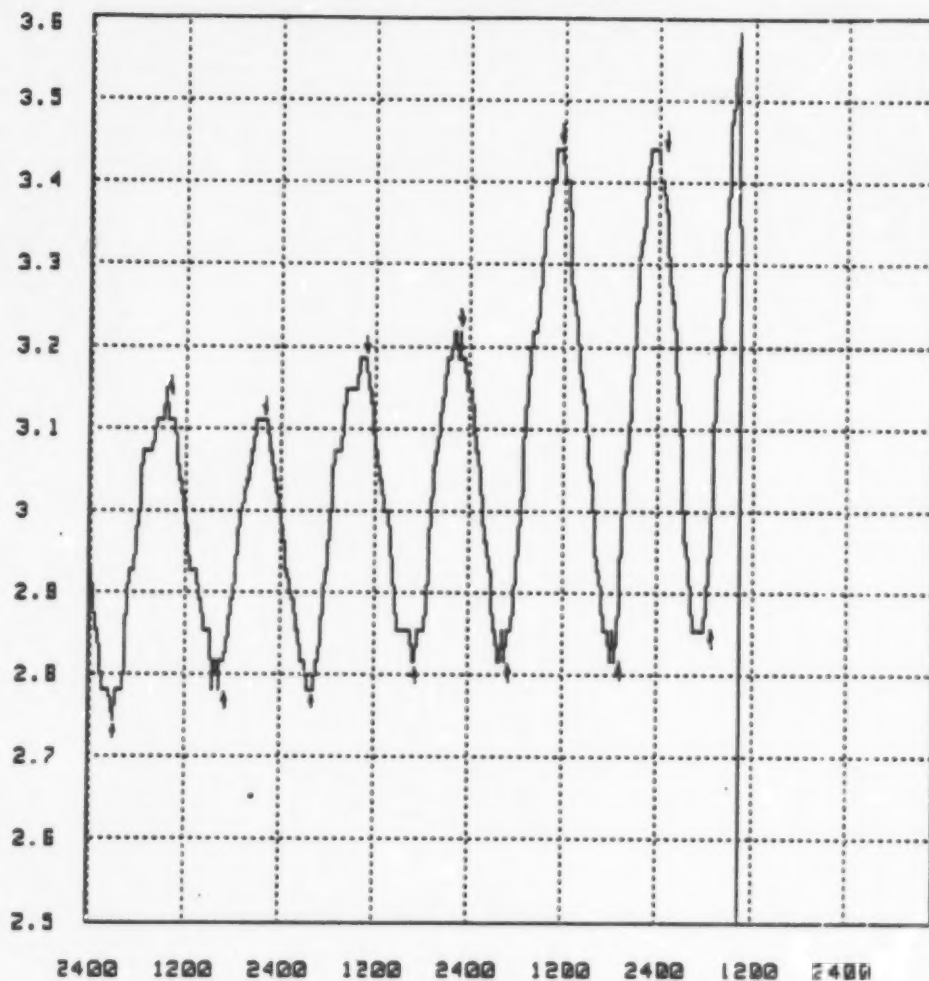


```
START DATE (DAY/MONTH) =2/1
  START TIME           =13:52
ENDING DATE (DAY/MONTH)=6/1
  ENDING TIME          =2:52
```

NANO CHANNELS

1

NANISIVIC TIDE DATA
DEPTH (METERS) VS TIME

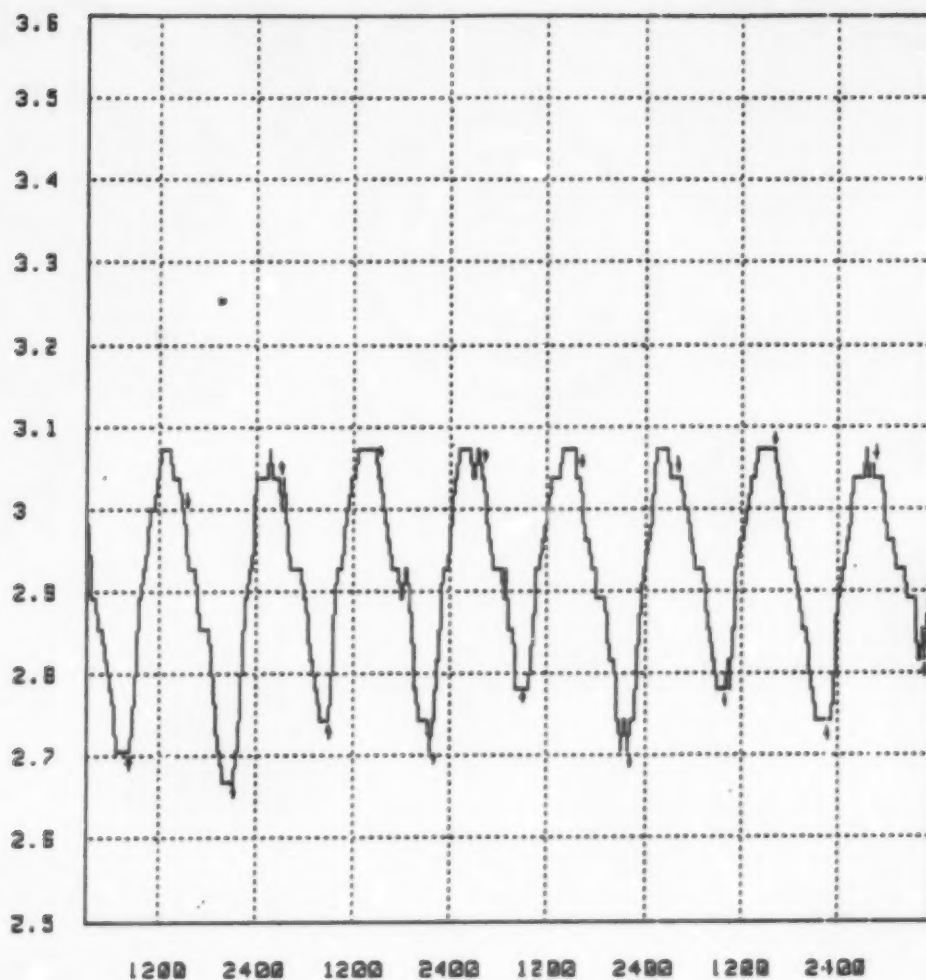


START DATE (DAY/MONTH) =14/1
START TIME =23:37
ENDING DATE (DAY/MONTH)=19/1
ENDING TIME =11:7

NAN3 CHANNELS
1

NANISIVIC TIDE DATA

DEPTH (METERS) VS TIME



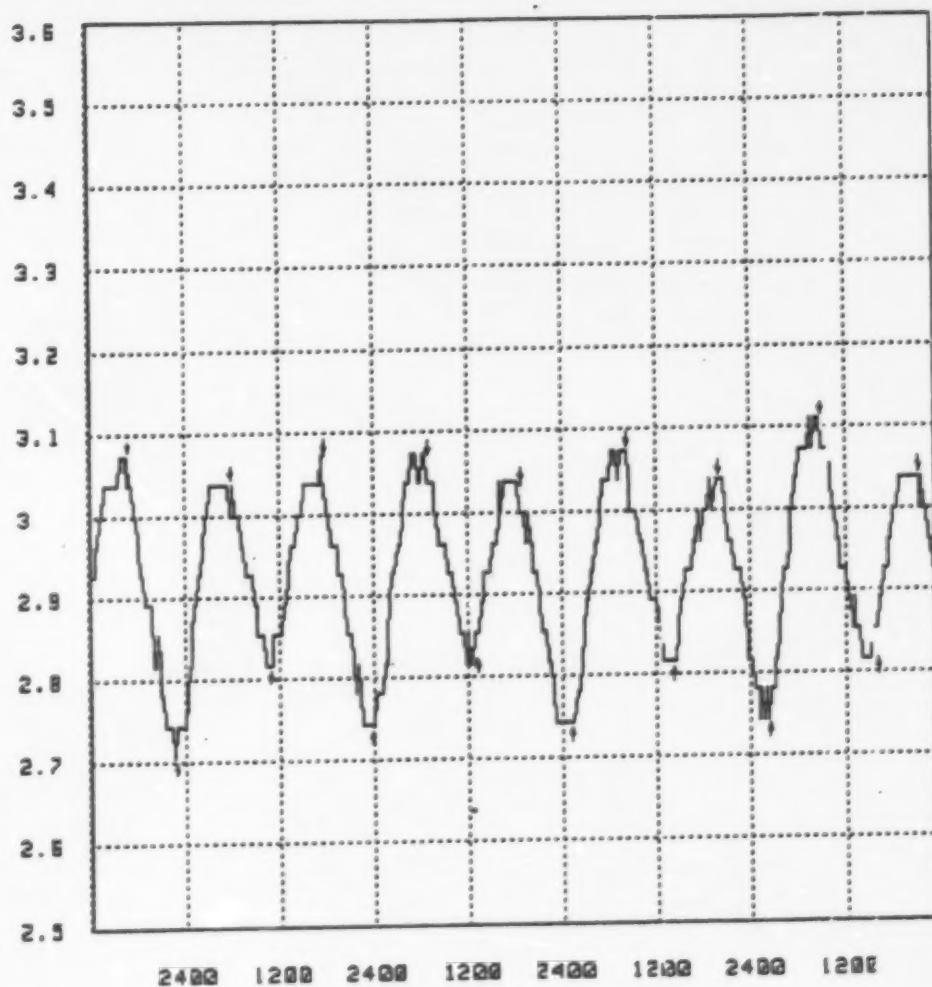
START DATE (DAY/MONTH) =6/1
START TIME =3:7
ENDING DATE (DAY/MONTH)=10/1
ENDING TIME =11:52

NAN1 CHANNELS
1

FIGURE 6.4

HANISIVIC TIDE DATA

DEPTH (METERS) VS TIME



```
START DATE (DAY/MONTH) =10/1
START TIME              =12:7
ENDING DATE (DAY/MONTH)=14/1
ENDING TIME              =23:22
```

NAN2 CHANNELS

1

A P P E N D I X C

BASIN ICE CONDITIONS DATA

Ice Physical Properties

The following ice physical properties were measured during the test program:

- ° ice thickness
- ° ice temperature
- ° ice salinity

The ice thickness was measured at a number of locations over the test site both at the commencement of the test program when the individual sensors were installed and at the completion of the test program when the sensors were removed from the ice sheet. Ice thicknesses were measured using a calibrated rod. Table 1 summarizes the ice thickness data that was collected.

The ice temperature was measured using two strings of seven thermistors each which were frozen in the ice sheet. One string was sited within 2 m of the reaction structure under the refrigeration mats while the other was located approximately 25 m from the structure in the middle of the ice sheet. Yellow Springs Instrument Co. (YSI) type 44005 thermistors were used. The individual thermistor resistances were recorded manually using a digital voltmeter. Table 2 summarizes the ice temperatures that were measured.

The ice salinity was determined at the end of the test program by measuring the electrical conductivity of melted ice samples. Measurements were made using a YSI model 33 conductivity meter. Table 3 summarizes the ice salinities that were measured.

TABLE 1
ICE THICKNESS DATA

DATE	LOCATION	ICE THICK (m)	COMMENTS
Feb. 27-28	Instrumented area of ice sheet in front of reaction structure	0.50-0.53	All sensors installed at this time except IRAD gauge and ARCO sensors AR41, AR42 and AR.
March 7	IRAD Gauge	0.51	Sensor installed
March 20	North slot:		
	a) at reaction structure	0.61	Measured immediately after slots were cut
	b) 1m from reaction structure	0.72	
	c) 2m from reaction structure	0.64	
	d) 3m from reaction structure	0.67	
	e) 4m from reaction structure	0.61	
	f) 5m from reaction structure	0.57	
	g) 6m from reaction structure	0.47	
	South Slot:		
	a) at reaction structure	0.57	
	b) 1m from reaction structure	0.61	
	c) 2m from reaction structure	0.63	
	d) 3m from reaction structure	0.70	
	e) 4m from reaction structure	0.67	
	f) 5m from reaction structure	0.50	
	g) 6m from reaction structure	0.52	
March 21	FEN1 and FEN2 site	0.49	Sensor Removed
	Mobil #1 site	0.46	Sensor Removed
	Mobil #2 site	0.62	Sensor Removed
	Mobil #3 site	0.57	Sensor Removed
	CMEL #1 site	0.65	Sensor Removed
	CMEL #2 site	0.59	Sensor Removed
	ARCO #1 site	0.58	Sensor Removed
	ARCO #2 site	0.60	Sensor Removed
	ARCO #3 site	0.57	Sensor Removed
	Medof Panel site	0.59	Sensor Removed
	IRAD guage site	0.59	Sensor Removed
	Weir-Jones Panel site	0.61	Sensor Removed
	EPR Panel #1 site	0.70	Sensor Removed
	EPR Panel #2 site	0.71	Sensor Removed
	ACL Hexpack	0.81	Sensor Removed

Note: 1 - See main volume for sensor locations.

TABLE 2
ICE TEMPERATURE DATA

Time (hrs)	Date of Measurement	TEMPERATURE (°C) NEAR STRUCTURE										TEMPERATURE (°C) AT MIDDLE OF BASIN									
		Material/Depth (m) Below Ice Surface										Material/Depth (m) below Ice Surface									
		Air	Ice	Ice	Ice	Ice	Ice	Ice	Ice	Water	Air	Ice	Ice	Ice	Ice	Ice	Ice	Ice	Ice	Water	Water
		0	0.05	0.15	0.25	0.35	0.50	0.80	0	0.80	0	0.05	0.15	0.25	0.35	0.50	0.80				
1600	March 02	+1.0	-9.3	-6.9	-5.0	-3.2	-0.9	-0.4	+1.5	-0.1	-1.0	-1.0	-1.0	-1.0	-1.0	-0.4	-0.4				
1600	March 03	-9.5	-3.5	-4.0	-3.5	-2.5	-0.8	-0.4	+2.0	-0.1	-1.0	-1.0	-1.0	-1.0	-1.0	-0.5	-0.4				
0900	March 04	-13.3	-4.6	-4.0	-3.1	-2.0	-0.8	-0.4	-3.9	-2.9	-1.8	-1.1	-1.0	-1.0	-0.6	-0.4					
0800	March 05	-7.8	-2.6	-2.7	-2.6	-1.9	-0.8	-0.4	+0.3	-1.2	-1.4	-1.2	-1.2	-1.2	-0.4	-0.4					
0745	March 06	-15.5	-4.3	-2.7	-2.1	-1.7	-0.8	-0.4	-3.1	-2.8	-0.8	-0.8	-0.8	-0.8	-0.6	-0.4					
1200	March 06	+0.4	-2.3	-2.7	-2.2	-1.9	-0.8	-0.4	+5.0	+1.0	-0.8	-0.8	-0.8	-0.8	-0.5	-0.4					
1540	March 06	+2.5	-1.5	-2.5	-2.3	-1.7	-0.7	-0.4	+0.9	+0.5	-0.6	-0.6	-0.6	-0.8	-0.4	-0.4					
0830	March 07	-7.6	-1.4	-1.8	-1.9	-1.6	-0.7	-0.5	-7.4	-1.2	-0.7	-0.8	-0.8	-0.8	-0.5	-0.4					
1145	March 07	-0.7	-1.5	-1.7	-1.8	-1.6	-0.7	-0.5	-2.3	-0.5	-0.5	-0.7	-0.7	-0.7	-0.4	-0.4					
1400	March 07	+5.0	-1.4	-1.9	-1.9	-1.5	-0.8	-0.4	+0.9	0.0	-0.4	-0.4	-0.4	-0.7	-0.5	-0.4					
0750	March 08	-3.2	-1.8	-1.9	-1.9	-1.6	-0.8	-0.4	-2.6	-0.8	-0.5	-0.7	-0.7	-0.7	-0.5	-0.4					
1050	March 08	-0.6	-1.9	-1.9	-1.9	-1.6	-0.8	-0.4	-1.2	-0.6	-0.6	-0.7	-0.7	-0.7	-0.6	-0.4					
0930	March 09	-13.5	-2.6	-2.1	-1.7	-1.4	-0.8	-0.4	-0.4	-0.8	-0.6	-0.6	-0.6	-0.7	-0.6	-0.4					
1800	March 09	-12.5	-1.5	-1.9	-1.8	-1.4	-0.7	-0.4	+9.3	+0.2	-0.6	-0.7	-0.7	-0.7	-0.6	-0.4					
1400	March 14	-14.5	-6.0	-5.7	-4.7	-3.3	-1.2	-0.4	-6.9	-1.7	-1.7	-1.4	-1.4	-1.0	-0.5	-0.4					
1000	March 20	+16.0	-1.7	-2.1	-2.0	-1.7	-1.0	-0.4	+4.5	+0.8	-0.2	-0.5	-0.5	-0.6	-0.5	-0.4					
1230	March 20	+7.0	-0.3	-1.7	-1.9	-1.7	-1.0	-0.3	+7.0	+0.8	-0.4	-0.6	-0.7	-0.6	-0.6	-0.3					

Notes: 1. The thermistor string near the structure was under the refrigeration mats for all test days except March 20. As can be seen from the above table, this has influenced the measured surface temperatures.

ICE SALINITY DATA

SAMPLE LOCATION AND DESCRIPTION ₁	Sample Depth in Ice Sheet (m)	Sample Salinity (ppt)
CMEL 1 - Backfill ice ₂	0-0.3	2.0
CMEL 1 - Backfill Ice	0.3-0.5	3.6
CMEL 1 - Undisturbed sheet ice near sensor	0-0.3	2.0
CMEL 1 - Undisturbed sheet ice near sensor	0.3-0.5	1.3
ARCO Site #1-Undisturbed sheet ice near sensor	0-0.1	0.0
AR 12 -Undistrubed sheet ice near sensor	0.1	2.1
AR 11 -Backfill ice	0.1	2.9
AR 12 -Backfill ice	0.1	2.1
AR 16 -Undisturbed sheet ice near sensor	0.4	1.5
AR 16 -Backfill ice	0.4	1.9
AR 23 -Backfill ice	0.2	2.0
AR 26 -Backfill ice	0.4	1.4
AR 25 -Undisturbed sheet ice near sensor	0.4	1.5
AR 25 -Backfill ice	0.4	2.5
AR 32 -Backfill ice	0.3	1.1
AR 32 -Backfill ice	0.2	1.8
AR 32 -Undisturbed sheet ice near sensor	0.3	1.8
AR 32 -Undisturbed sheet ice near sensor	0.2	1.5
Ice core 6m from reaction structure at end of slot in ice sheet	0-0.1	0.1
	0.1-0.2	1.8
	0.2-0.3	1.8
	0.3-0.4	1.6
	0.4-0.5	1.2
Ice core in middle of basin approx. 25m from reaction structure	0-0.1	0.7
	0.1-0.2	0.6
	0.2-0.3	1.7
	0.4-0.5	1.6
Ice core near reaction structure at BP site #1	0-0.1	1.0
	0.1-0.2	2.3
	0.2-0.3	2.1
	0.3-0.4	1.1
	0.5-0.6	1.9
Ice core approx. 6m from reaction structure. This ice core was analyzed on March 7 by BP personnel using their instruments ₃ .	0.02-0.03	0.3
	0.1-0.11	0.9
	0.2-0.21	1.4
	0.3-0.31	2.0
	0.5-0.51	1.5
Ice core approx. 1m from reaction structure. This ice core was analyzed on March 8 by BP personnel using their instruments ₃ .	0.02-0.03	0.6
	0.13-0.14	1.8
	0.23-0.24	2.0
	0.33-0.34	1.8
	0.49-0.50	1.8

NOTES: 1. See main volume for individual sensor locations

2. Backfill ice refers to the refrozen slush which was packed around the sensor in the borehole during installation

3. All salinity measurements were made at the end of the test program on March 21 with the exception of the ice cores analyzed by BP personnel